Kobe International School
of Planetary Sciences

Detection of Extrasolar Planets and Characteristics of the Host Stars

Debra Fischer

COEPS Roadmap:

The origin of planetary systems through astronomical observations of extrasolar planets

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

This lecture focuses on detection and characterization of extrasolar planets

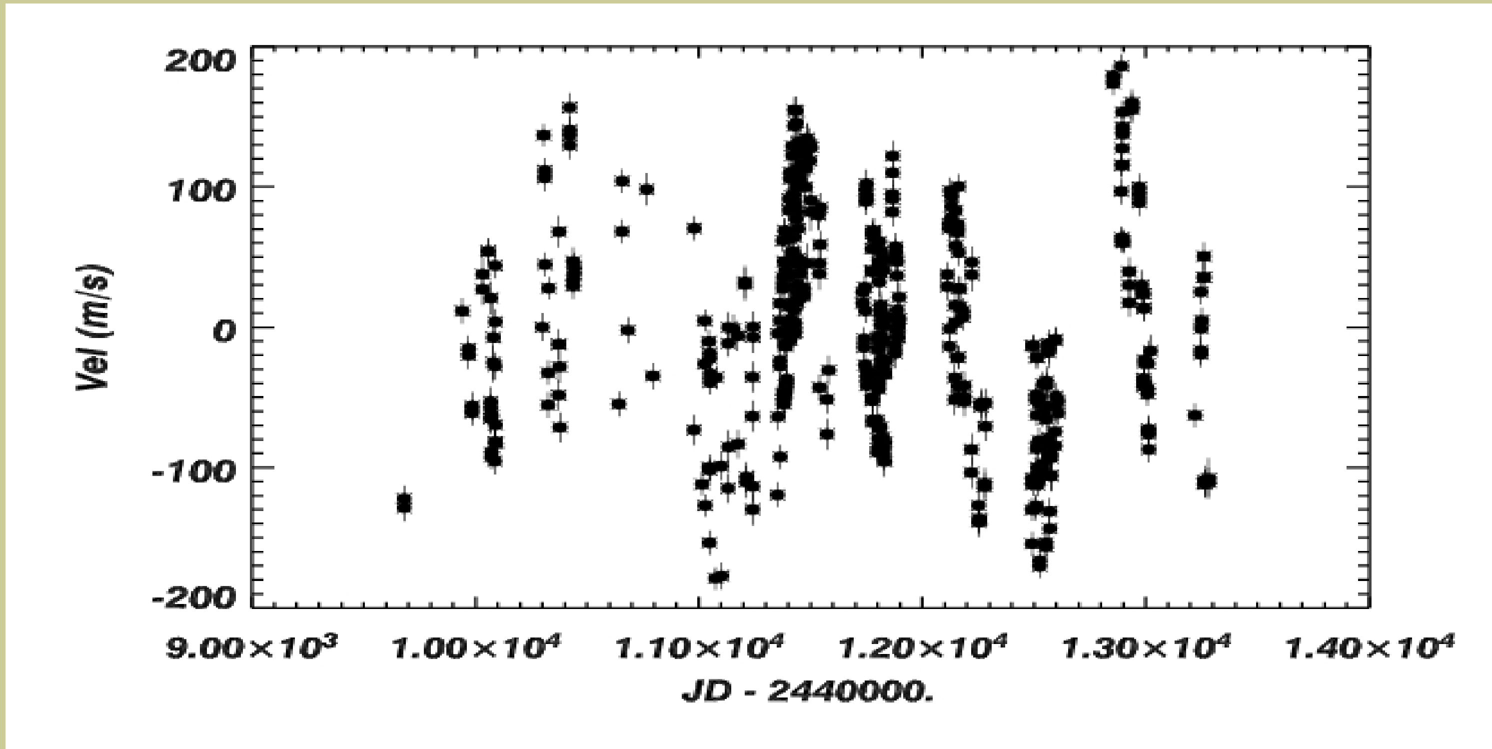
Organization of Lecture

- Overview of the Doppler Technique
  - Observational Parameter Space
  - Biases and incompleteness
- Statistical Summary of Planet Characteristics
- The Extrasolar Planet Zoo
- Multi-Planet Systems
- The Planet-Metallicity Correlation

What we "see" or imagine when an extrasolar planet is detected:

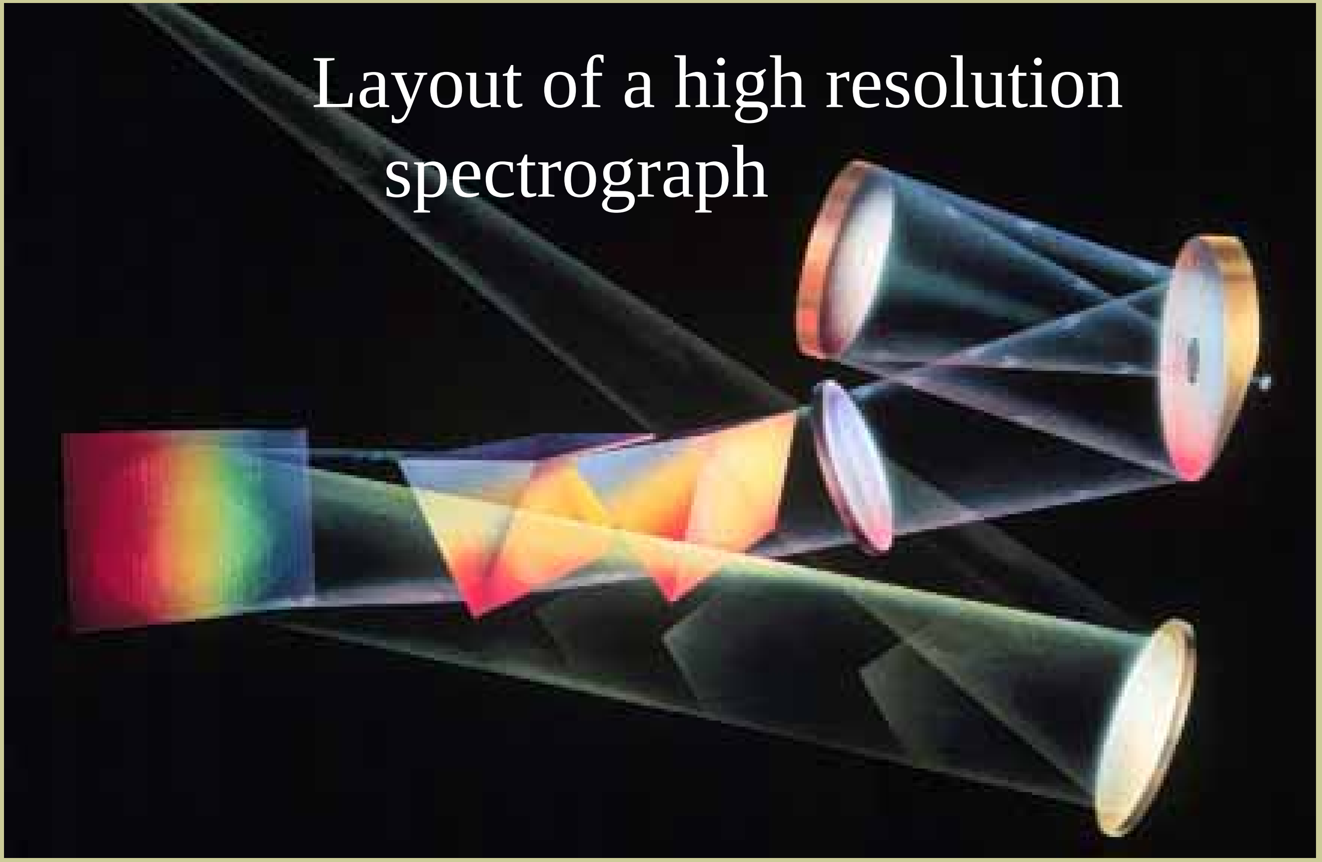
Artwork by Greg Laughlin, UCSC

What the Doppler technique "sees" when an extrasolar planet is detected:



The Doppler technique is the window through which we see the world of extrasolar planets. You should understand the biases and observational incompleteness of this technique.

Doppler Technique: background

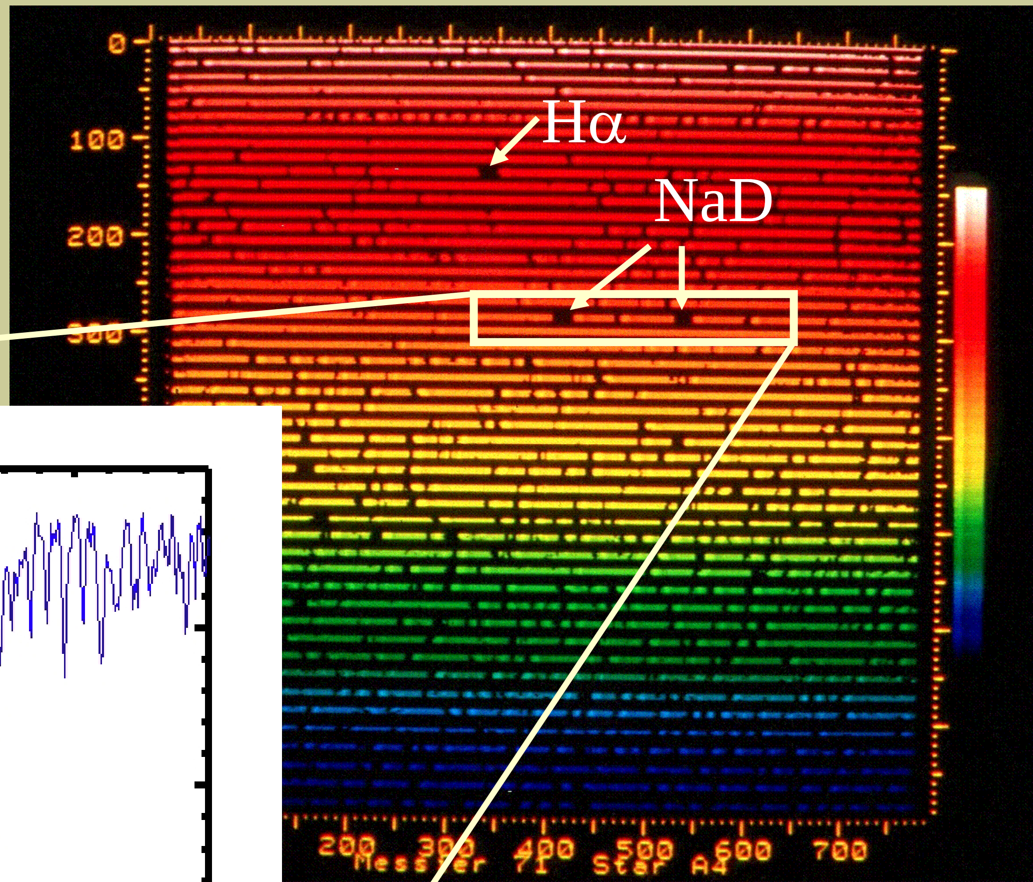


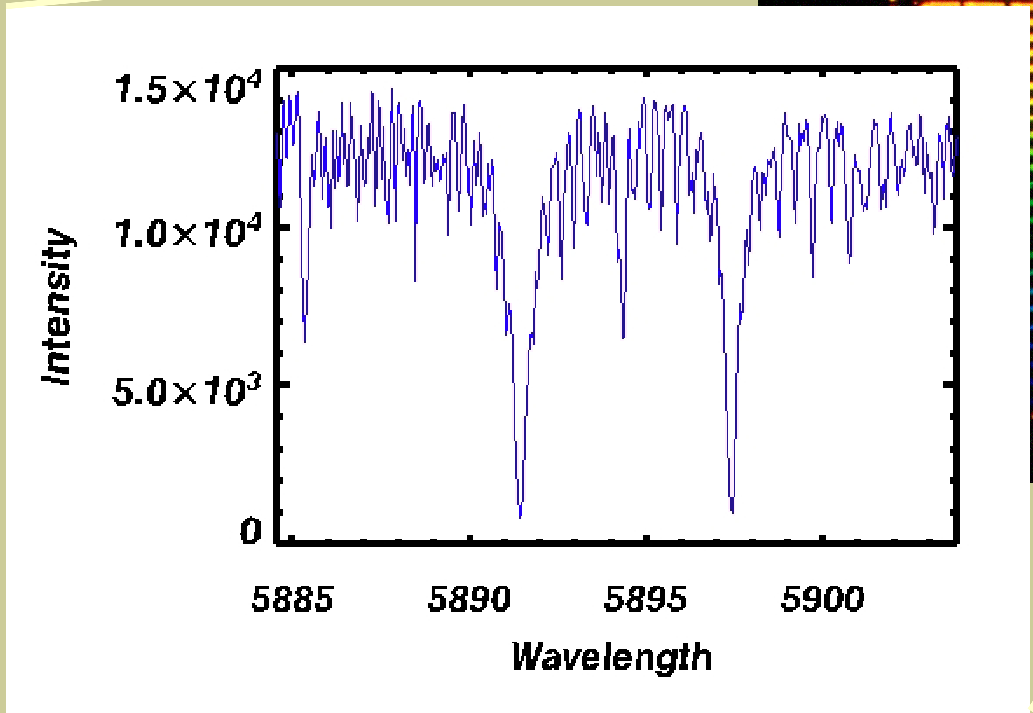
[See posters by Andrew Vanden Heuvel: “ET” instrument
Yoichi Itoh: Imaging Debris disks
Amaya Moro-Martin: Signatures of planets in debris disks
Kenta Fujita: SPICA]

Doppler Technique: background

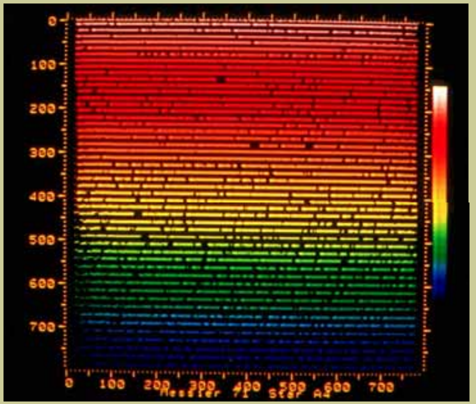
The spectrum is extracted from the 2-D echelle image, to give an array of intensity vs wavelength for each spectral order.

Echelle spectrum





Doppler Technique: background



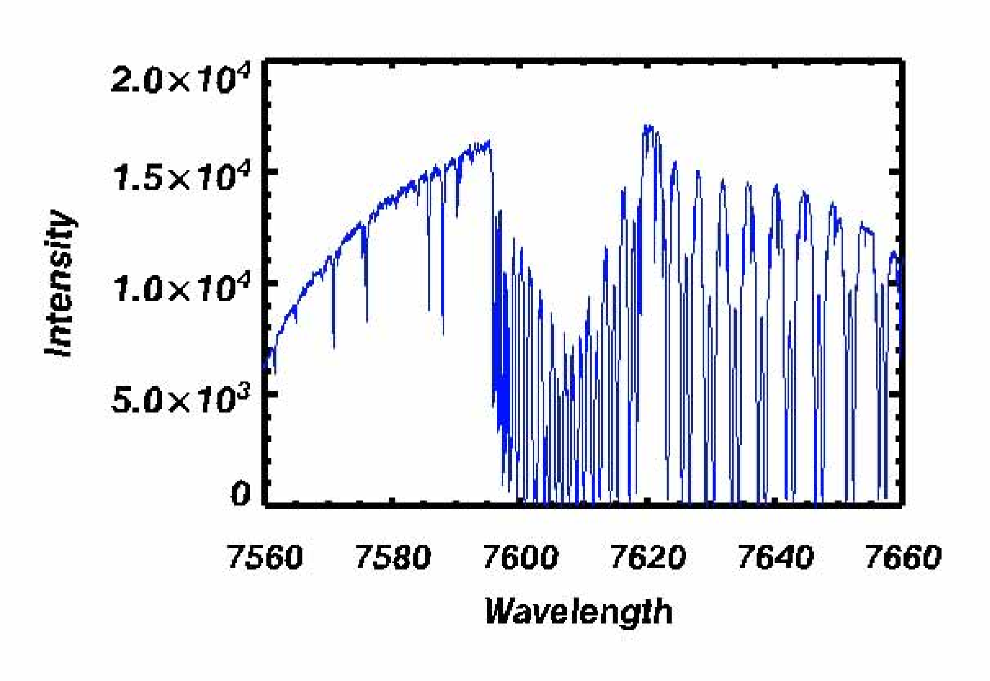
Atomic and molecular lines in the atmosphere of the star absorb light at particular wavelengths.

1) the intensity of spectral lines is determined by the optical depth of the absorbing species, regulated by temperature and element abundance.

2) Exploiting the Doppler effect, the releative velocity between the telescope and the star can be measured by measuring shifts in spectral lines:

$$\Delta\lambda/\lambda = v/c$$

Doppler Technique: background



"Telluric" lines from the Earths atmosphere (e.g., H_2O, O_2, OH) absorb starlight. The Earth's atmosphere absorbs at rest wavelengths, so telluric lines can serve as a reference for Doppler-shifted stellar lines. But, telluric lines are intrinsically broad and variable.

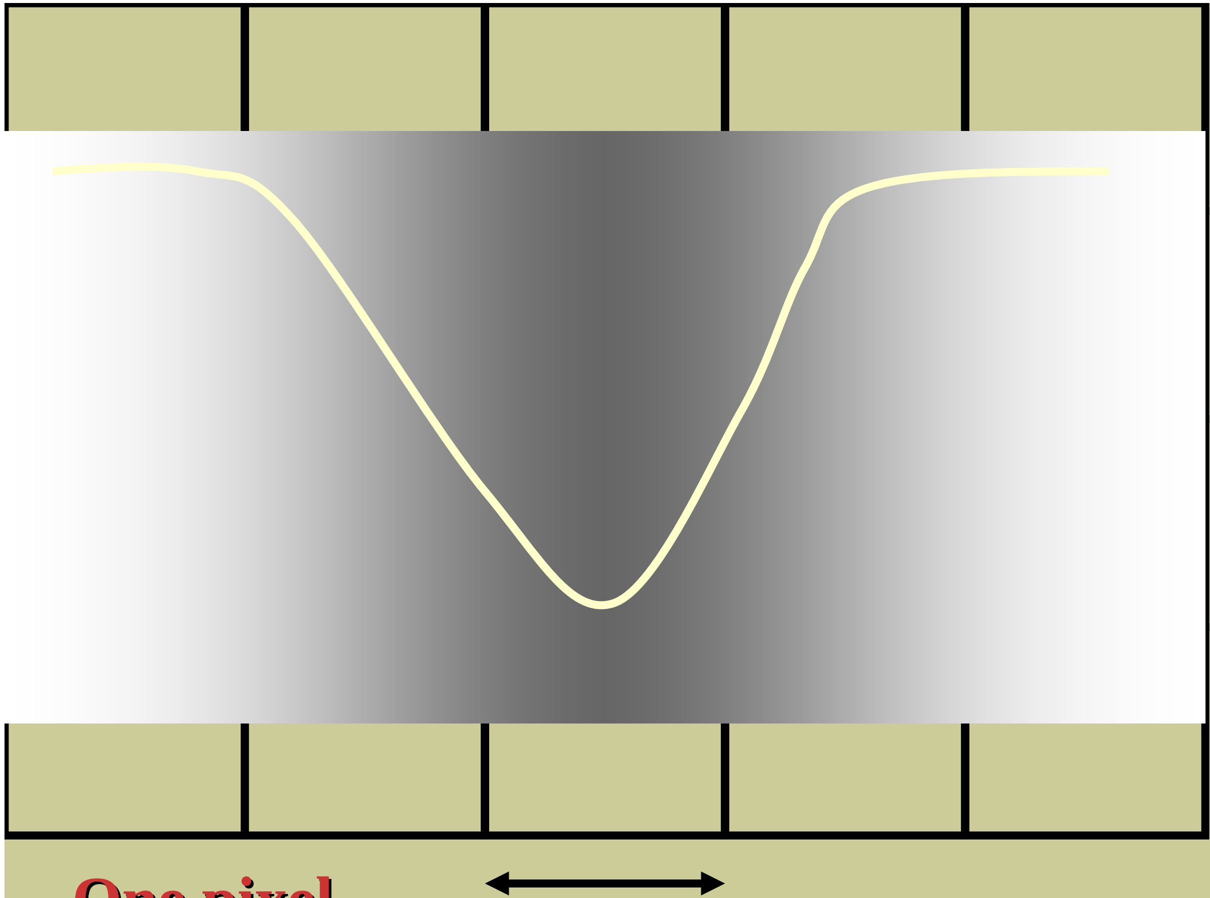
Shifts in stellar lines relative to telluric lines can only be measured to about 1/2 pixel precision… with a velocity precision of 1500 m/s. ***Not good enough!***

High Precision Doppler Measurements

The detection of extrasolar planets requires the highest precision Doppler measurements possible.

- Jupiter: induces a reflex velocity of ~12 m/s in the Sun.
- Earth: induces a reflex velocity of ~0.1 m/s in the Sun

For RV_{STAR} = 12 m/s, $\delta\lambda$ ~ 0.0002 Angstroms



One pixel

Physical dimension: 15 μ

Dispersion λ: 0.05 A

Velocity: 3000 m/s

For typical high resolution spectrographs with 15 μ-pixel CCD detectors (HDS on Subaru or HIRES on Keck), $\delta\lambda = 0.0002$ A corresponds to 0.004 pixel shift. To measure this signal, you need a precision that is many times better.

Note: typical spectral lines are 0.1 - 0.2 Angstroms (or a few CCD pixels) in width, so we need to detect shifts approaching 1/1000 of the lines we model.

High Precision Doppler Measurements

Technical challenges to high precision:

• Instrumental smearing (PSF) that varies over the format of the detector.

• Electronic noise and charge diffusion in the detector.

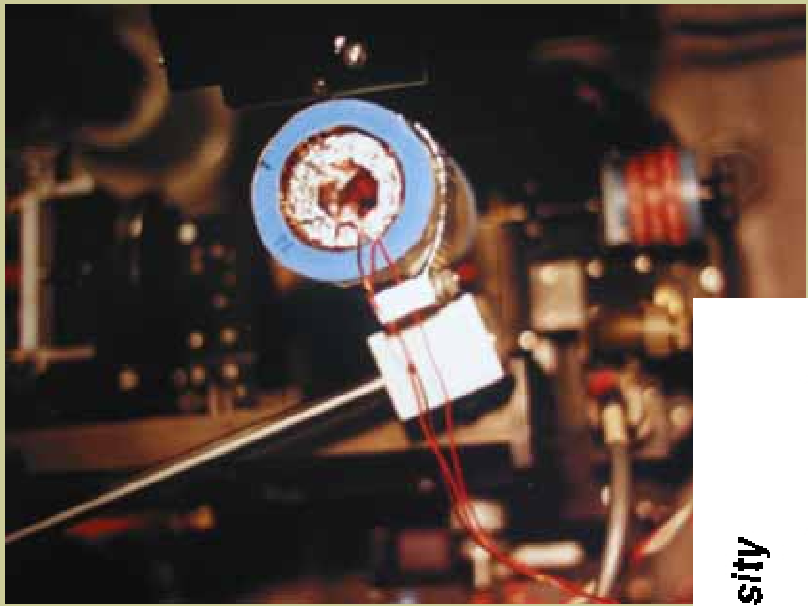
• Stability of the spectrograph (anticipate sub-pixel drifts through the night and between observing runs).

• Precise, high-order wavelength solution for the detector

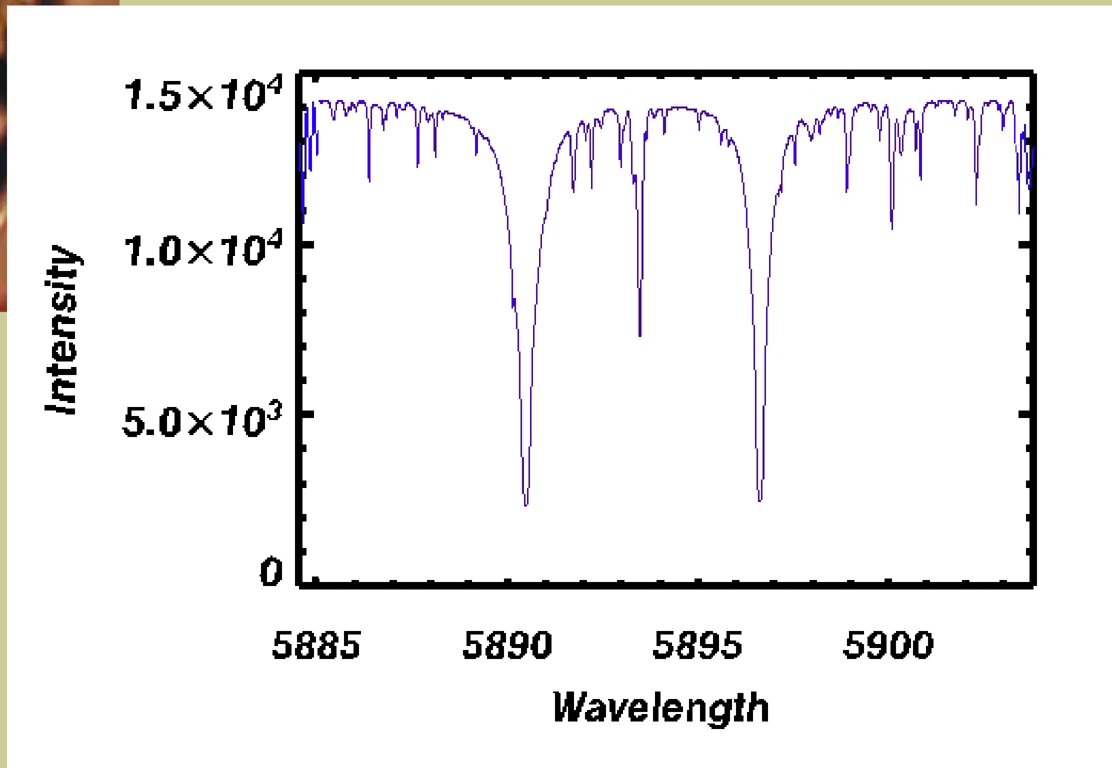
• Photon noise

Can't position the spectrum to $\frac{1000}{1}$ ***of a pixel, so how can*** $\delta\lambda$ ***be measured with the required precision?***

High Precision Doppler Measurements



We impose our own reference spectrum on the stellar spectrum with an iodine cell: shallow, narrow lines that span 1000 Angstroms.



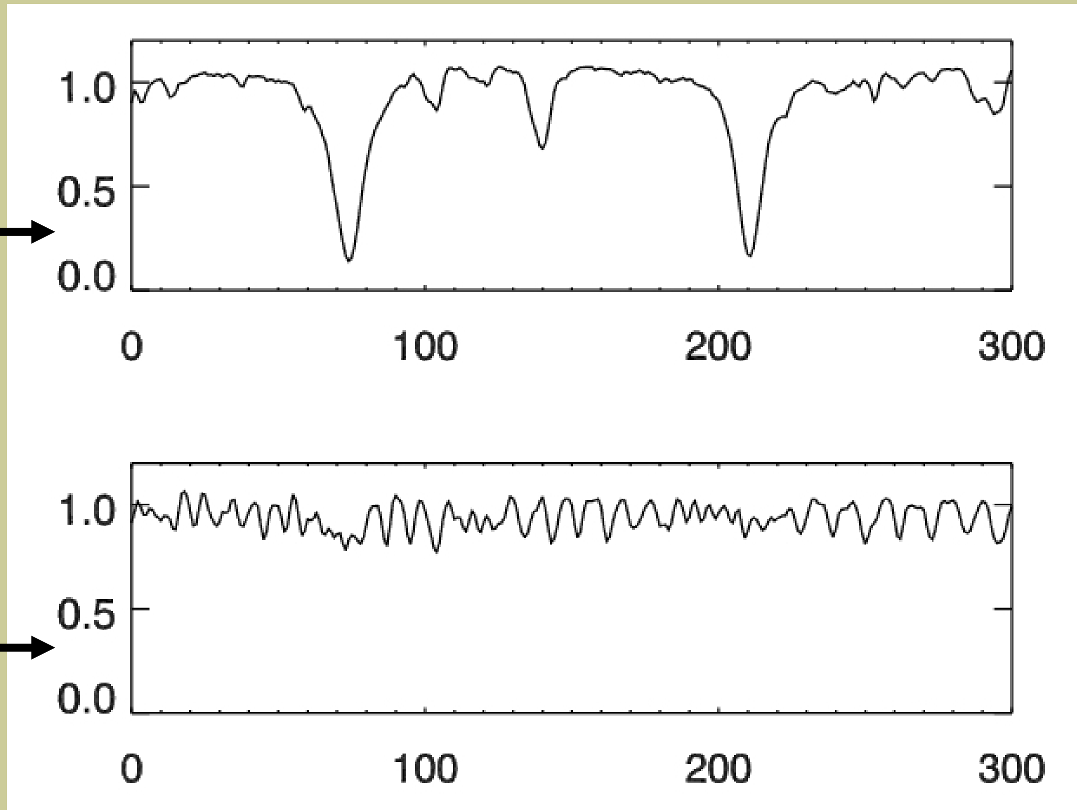
A closer look at a snip of spectra around the Na D lines shows a forest of I2 lines in our observations.

High Precision Doppler Measurements

Modeling the wavelength shift and PSF

1) High S/N, high resolution "Template" spectrum for each star

2) High S/N, high resolution Iodine spectrum (FTS, R=500000)

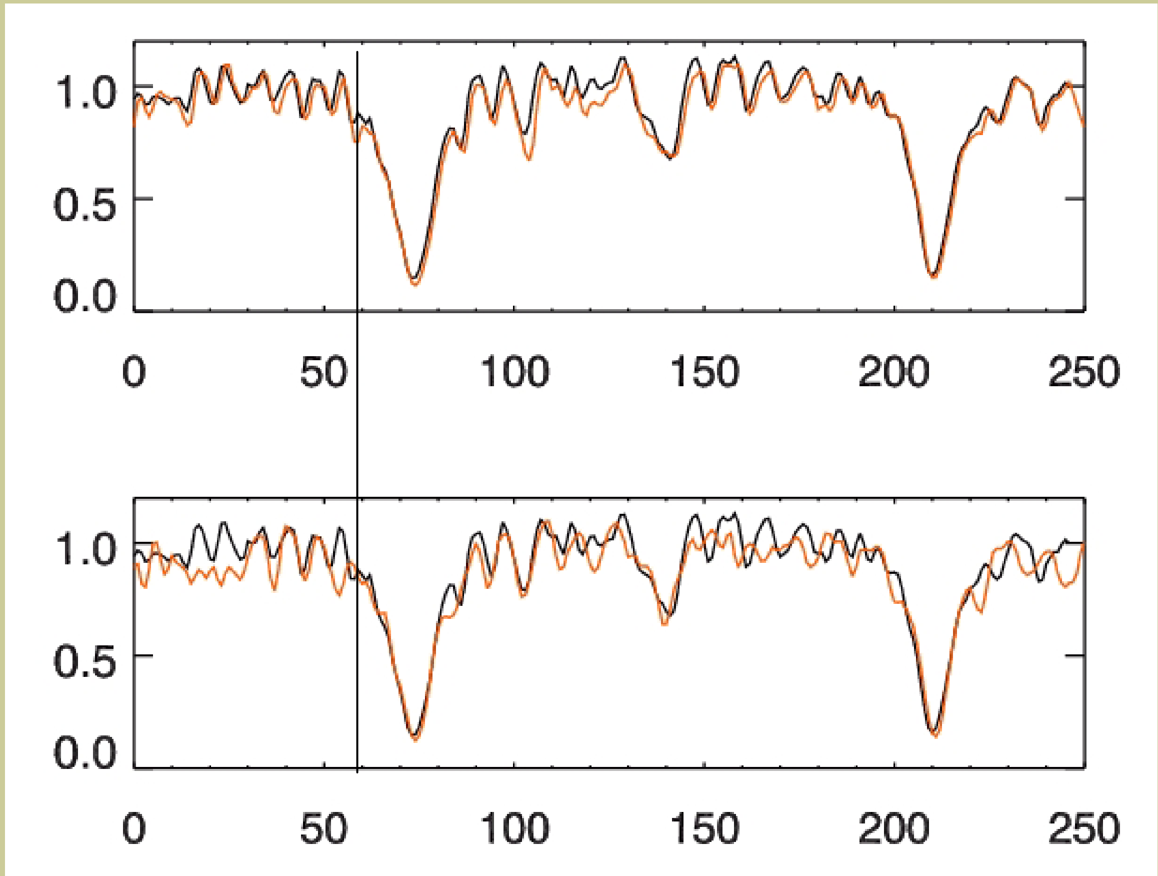


[See posters by Eri Toyota: Search for extrasolar planets in binary systems and Yujuan Liu: Search for planets around G giants.

High Precision Doppler Measurements

The template spectrum is multiplied by the iodine spectrum to create a model spectrum for each observation. Wavelength shift and instrumental broadening are free parameters.

In these two figures, the observed spectrum is shown in black with two models (different wavelength shifts) over plotted in red. The best fit is determined by χ^2 test.



This strategy can produce a single-measurement Doppler precision of ~1 m/s

High Precision Doppler Measurements

Astrophysical challenges:

~~OBA stars~~

- FGKM stars are suitable targets;
  - massive stars are too hot and have few spectral lines
  - OBA stars are also rapidly rotating
- Variability in the stellar photosphere

~~Chromospheric activity~~

- Rapid rotation

~~Broad spectral lines~~

Astrophysical challenges:

Variability from the stellar photosphere

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Convective dynamos spawn magnetic fields and result in spots and flares with ~km/s outflows producing convective blue shifts in spectral line profiles.

These arise from the photosphere and are not dynamical Doppler shifts, but how to tell the difference?

Note: this is the “chromospherically quiet” Sun!

Astrophysical challenges:

Variability from the stellar photosphere

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Long term cycles in the magnetic fields may also be associated with cycles in photospheric velocities - a non-dynamical source of RV variation.

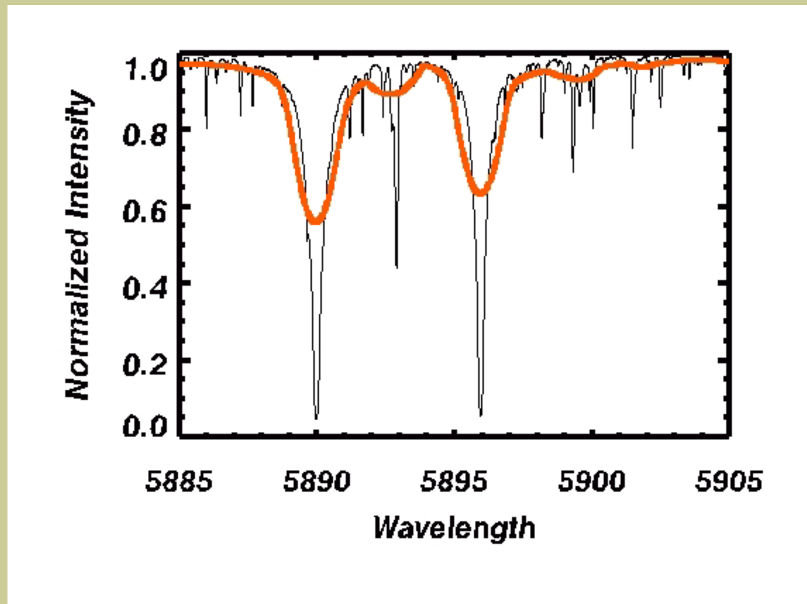
Modeling Ca H&K line emission can at least serve to warn you - but we don’t have a good correction yet.

Again, this is the quiet, steady old Sun!

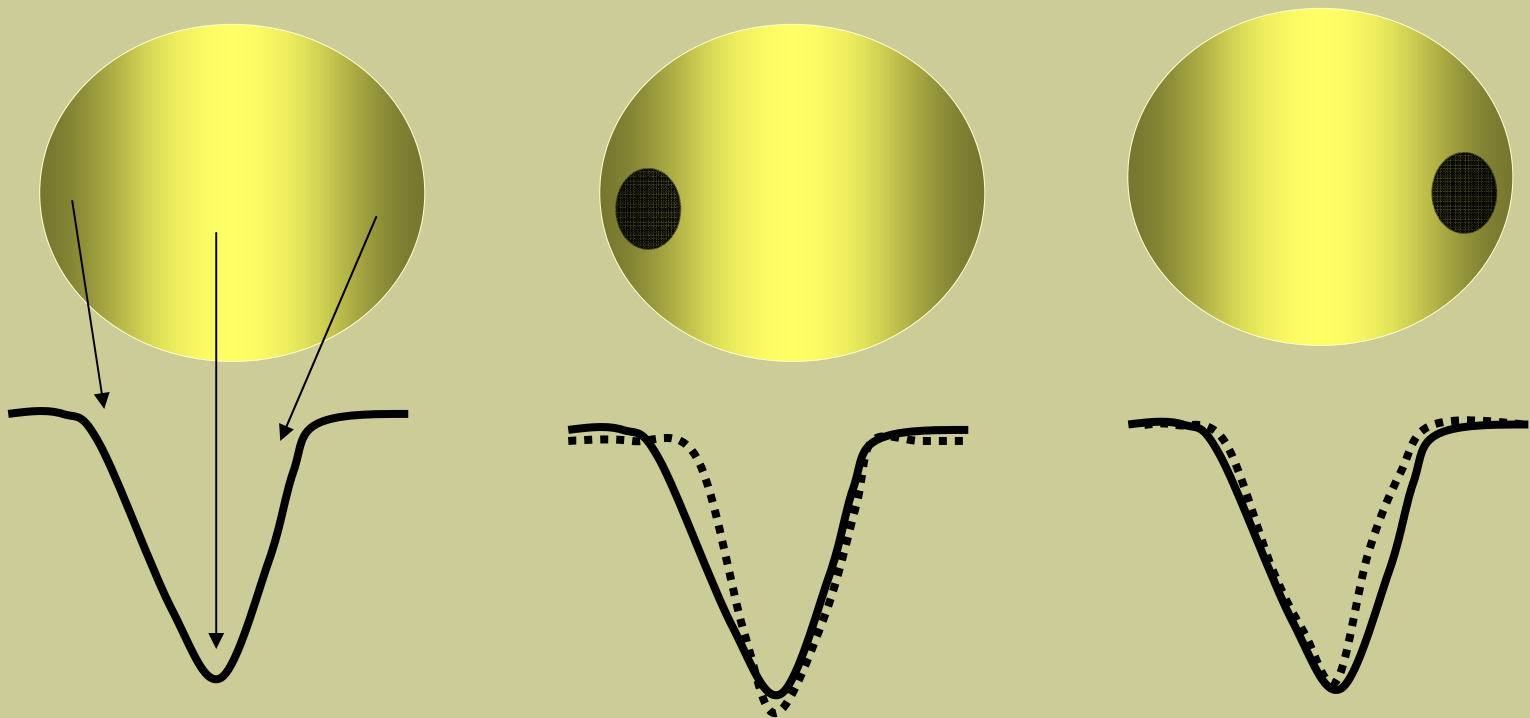
Astrophysical challenges:

High Rotational Velocities

Leads to poorer precision in centroiding stellar lines to measure $\delta\lambda$.



High rotational velocities are associated with chromospheric activity and starspots. As starspots rotate across the star, the line centroid shifts.



These astrophysical challenges to Doppler precision are likely to be problems for other detection techniques, too.

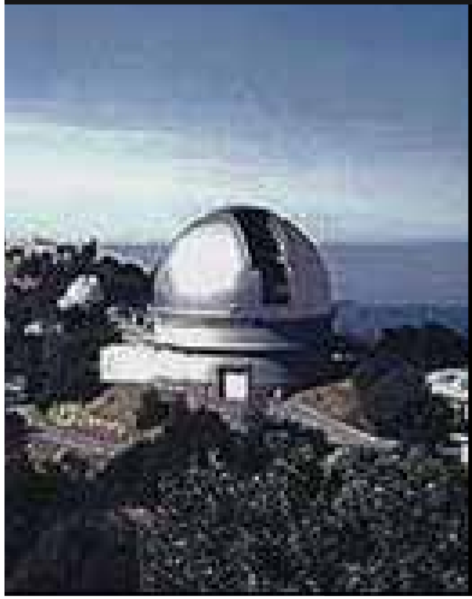
1300 FGKM Main sequence or subgiants

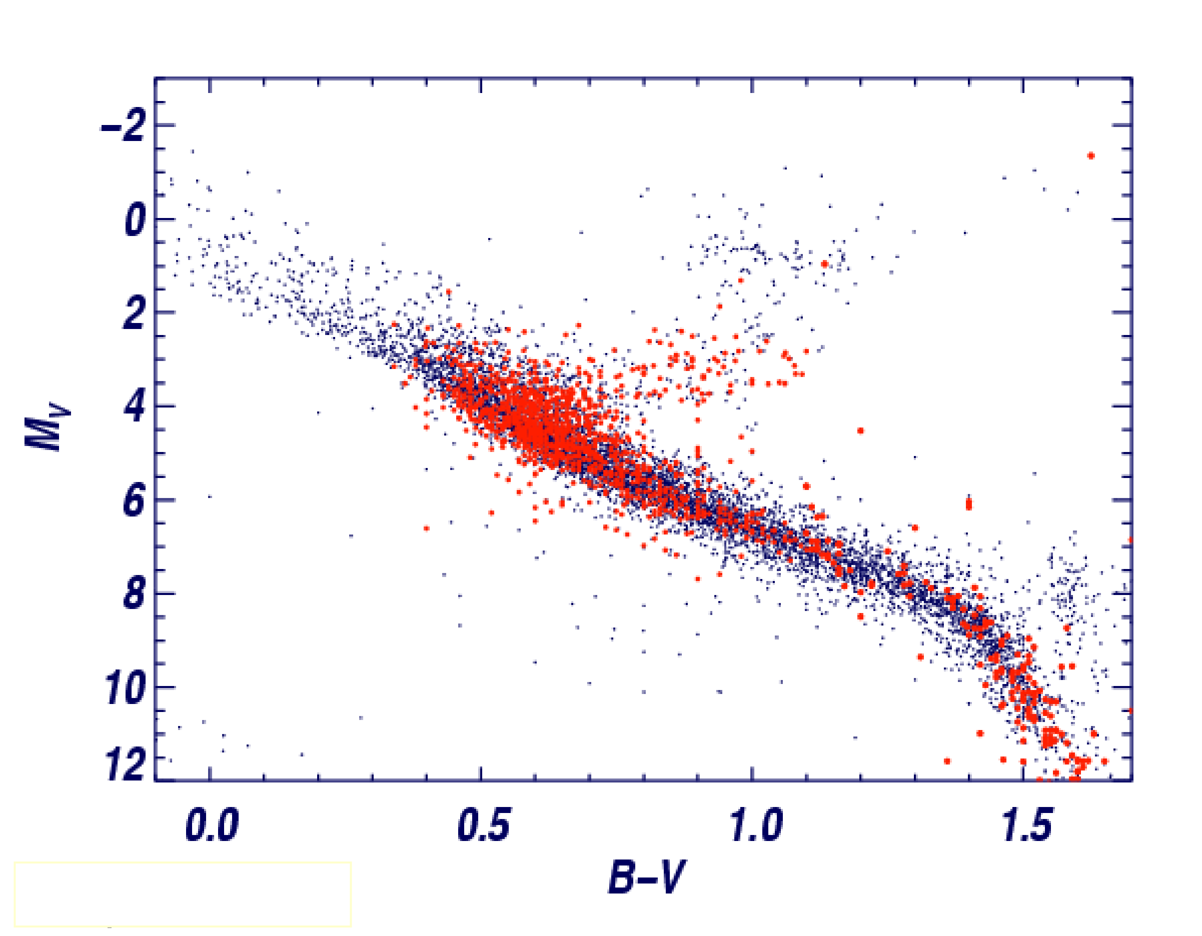
Vmag < 10

no close binaries

Age > 2 Gyr

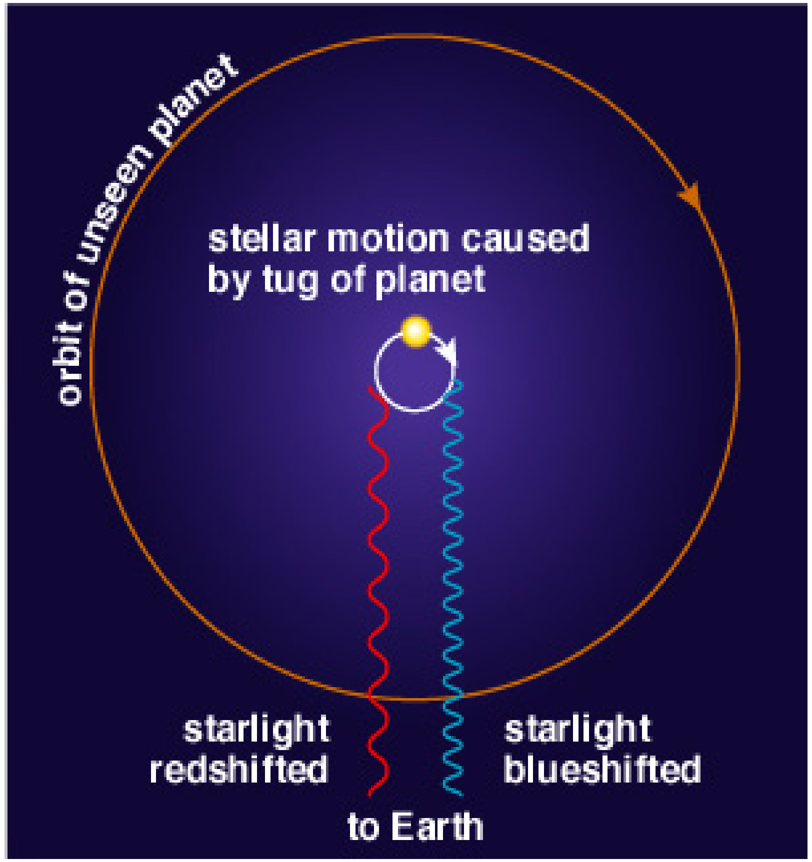
Lick	Keck	Magellan	AAT
1988	1997	2003	1998
(5 AU)	(3.1 AU)	(< 1 AU)	(2.9 AU)



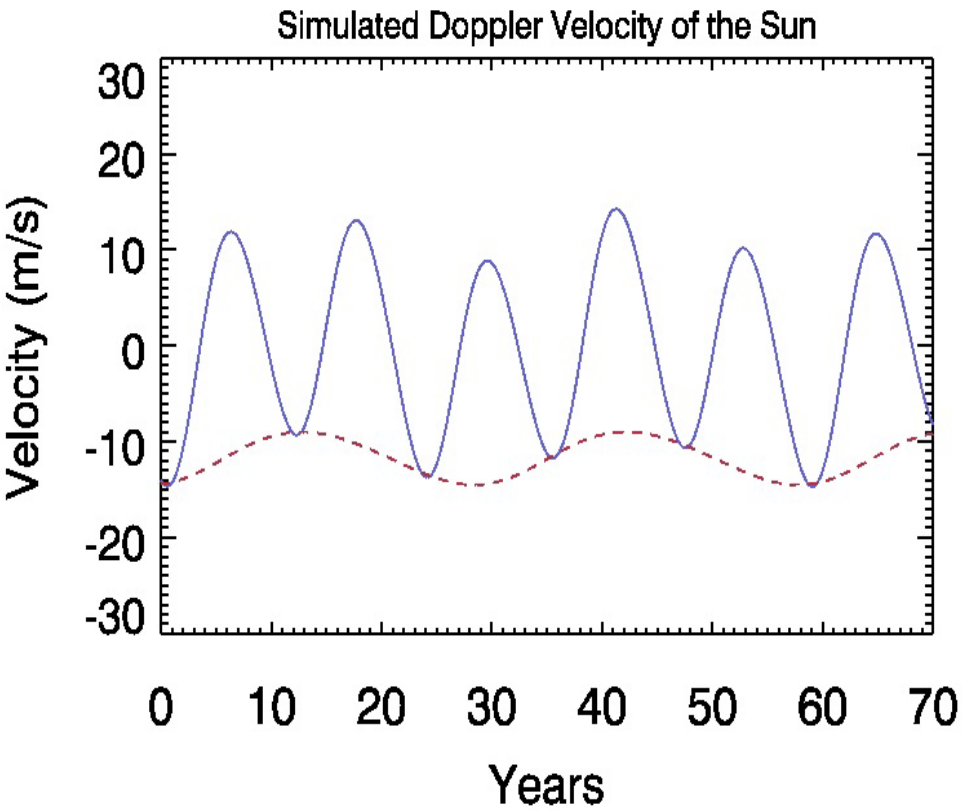



M_V
B−V

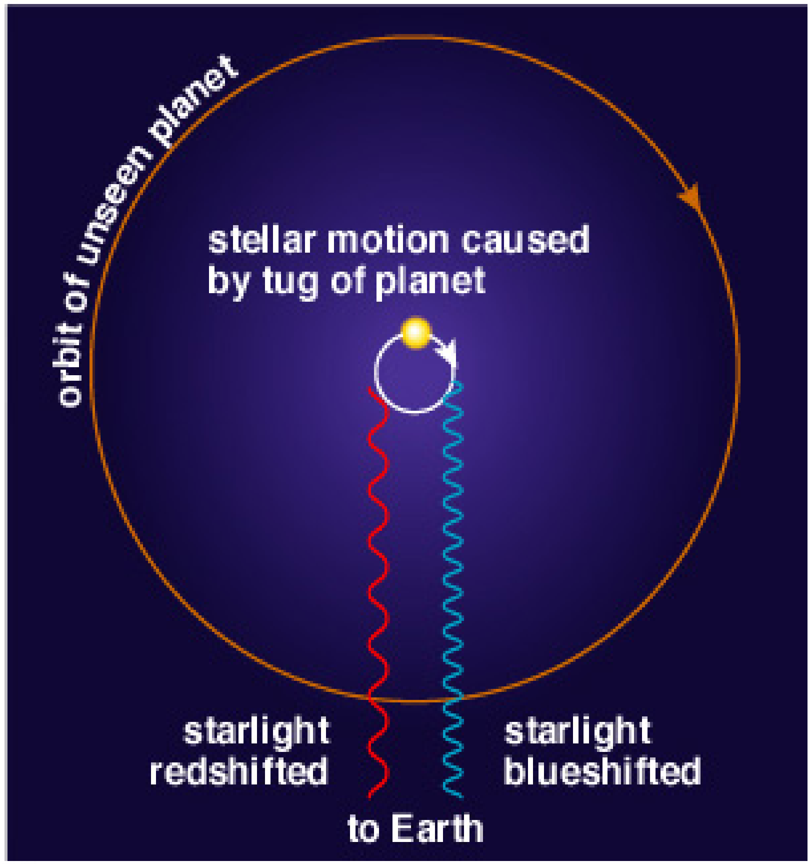
What our solar system would look like to the Doppler technique:



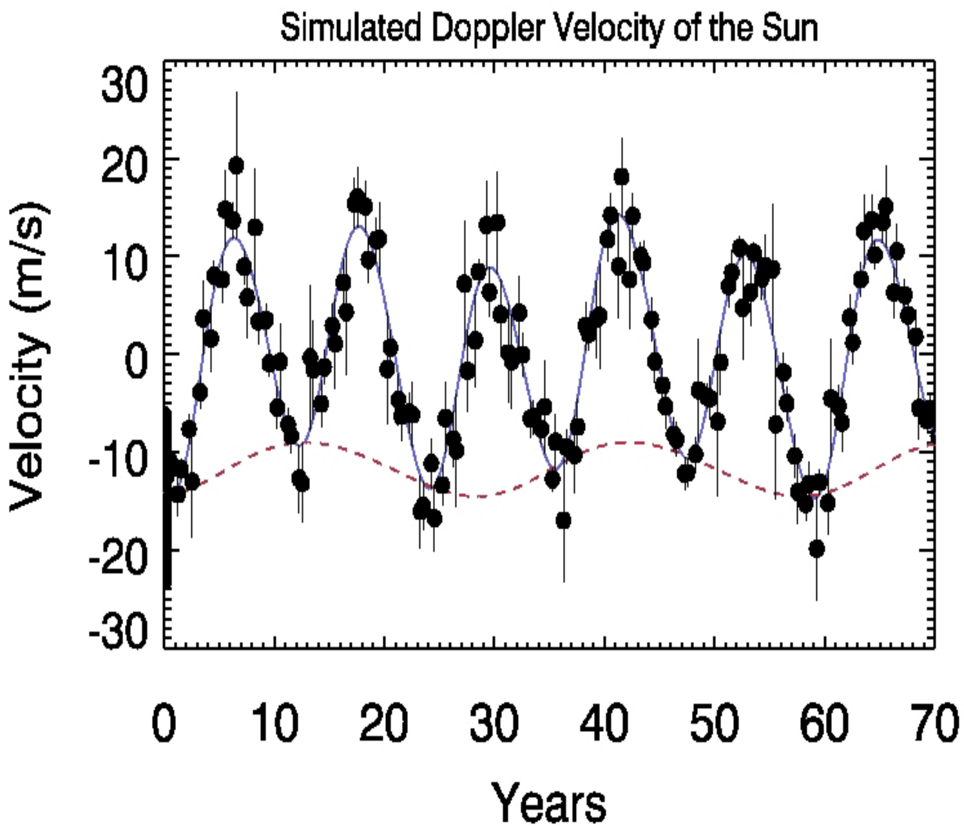
(a)



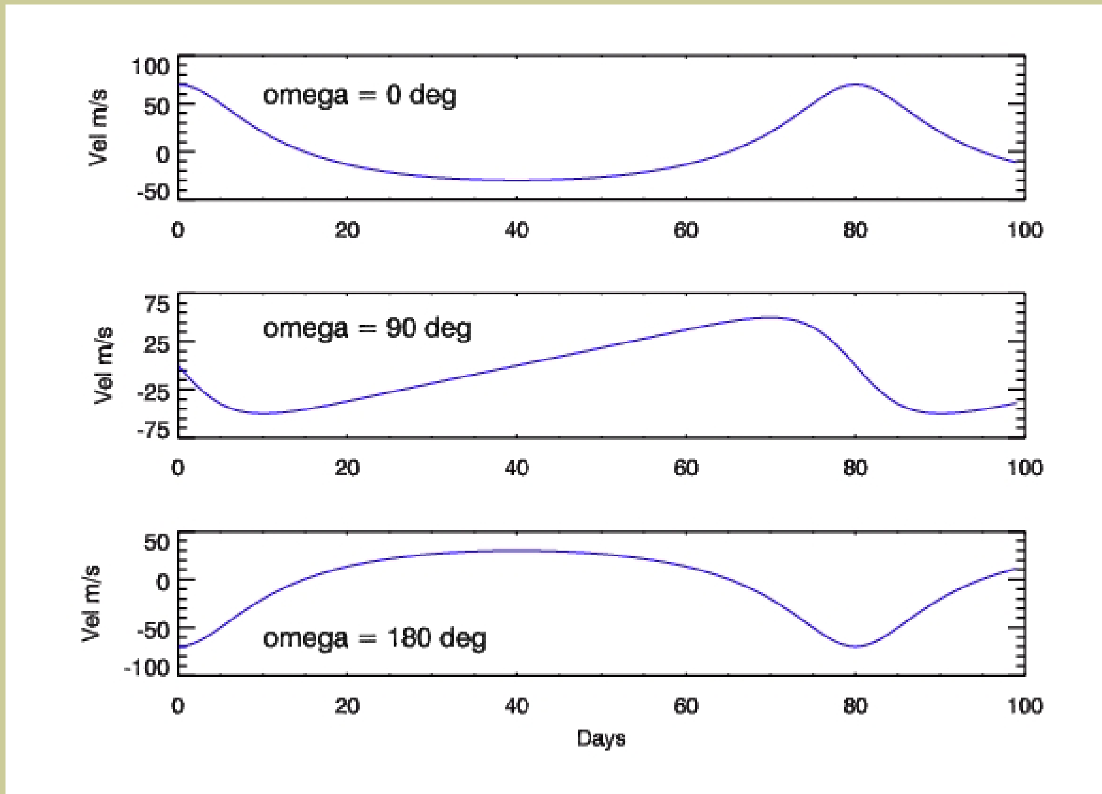
What our solar system would look like to the Doppler technique:



(a)



Orbital elements that can be modeled from Doppler observations: Orbital Period (P), Time of Periastron passage (T_P), eccentricity (e), omega (ω), Velocity semi-amplitude (K)



Inferred (depends on assumed stellar mass):

M_{PL}sini

Semi-major axis

Model: P=80d, Tp = 0, e = 0.4, K=50 m/s

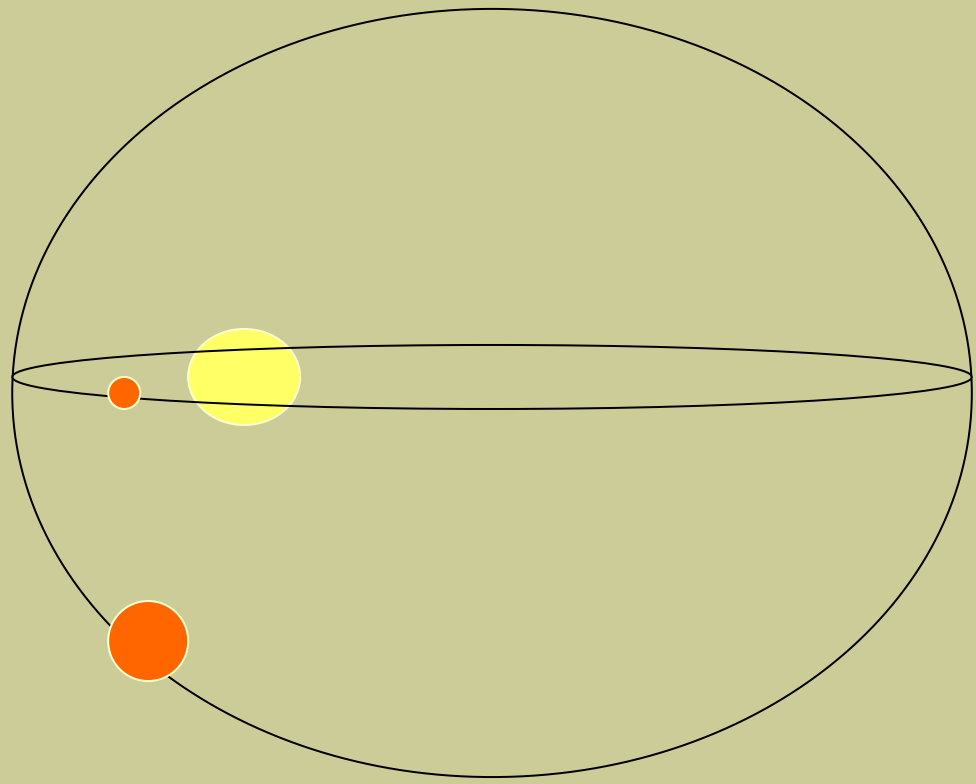
K = RV semi-amplitude

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p \sin i}{\left(M_p + M_*\right)^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

$$K_{circ} = 28.4 m s^{-2} \left(\frac{1 year}{P}\right)^{1/3} \left(\frac{M_p \sin i}{M_{Jup}}\right) \left(\frac{M_{sun}}{M_*}\right)^{2/3}$$

The Doppler technique measures Msini.

Orbital inclination cannot be determined so the Doppler planet mass is a lower limit (but, statistically within a factor of two of total mass).



We can’t measure the orbital inclination with the Doppler technique, but statistically the total mass is within a factor of two of Msini.

$$P(\Delta i) = \cos(i_1) - \cos(i_2)$$

Δ(i)	P(Δi)	M_{TOT}
0-30	13%	>2*Msini
30-90	87%	<2*Msini

The Next Decade:
3 m/s versus 1 m/s

3 m/s

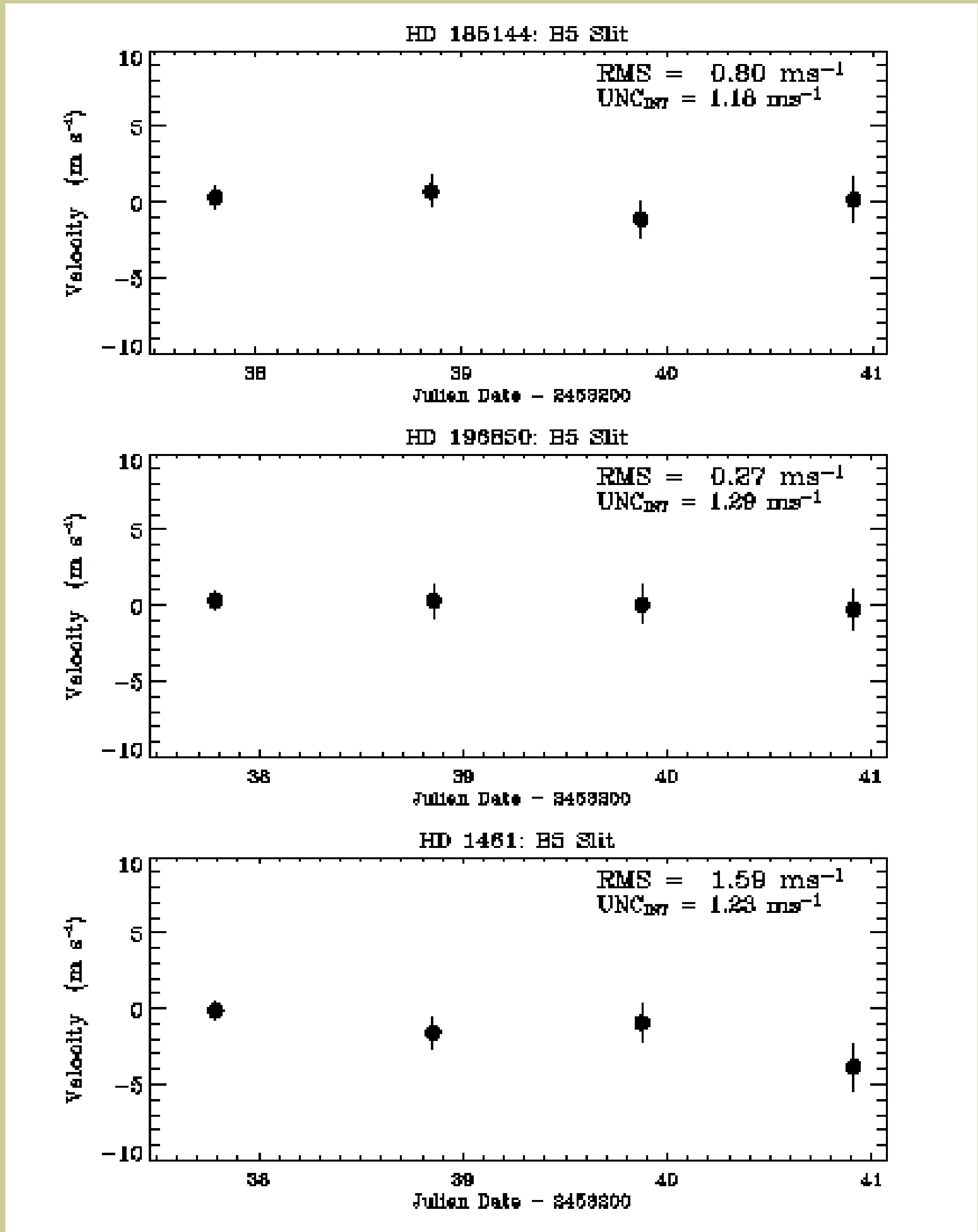
Minimal (3-sigma) detection of Jupiter analog
Eccentricity of Jupiter analog is uncertain (+/-0.2)
Non-detection of Saturn-mass at 5 AU

1 m/s

Jupiter analog is 10-sigma detection
Uncertainty of eccentricity is +/-0.02
Saturn-mass at 5 AU is a 4-sigma detection
Super-Earths detectable in 4-day orbits

Obstacles to 1 m/s

Stellar oscillations
Stellar granulation
Stellar rotation
Photons
Systematic Errors



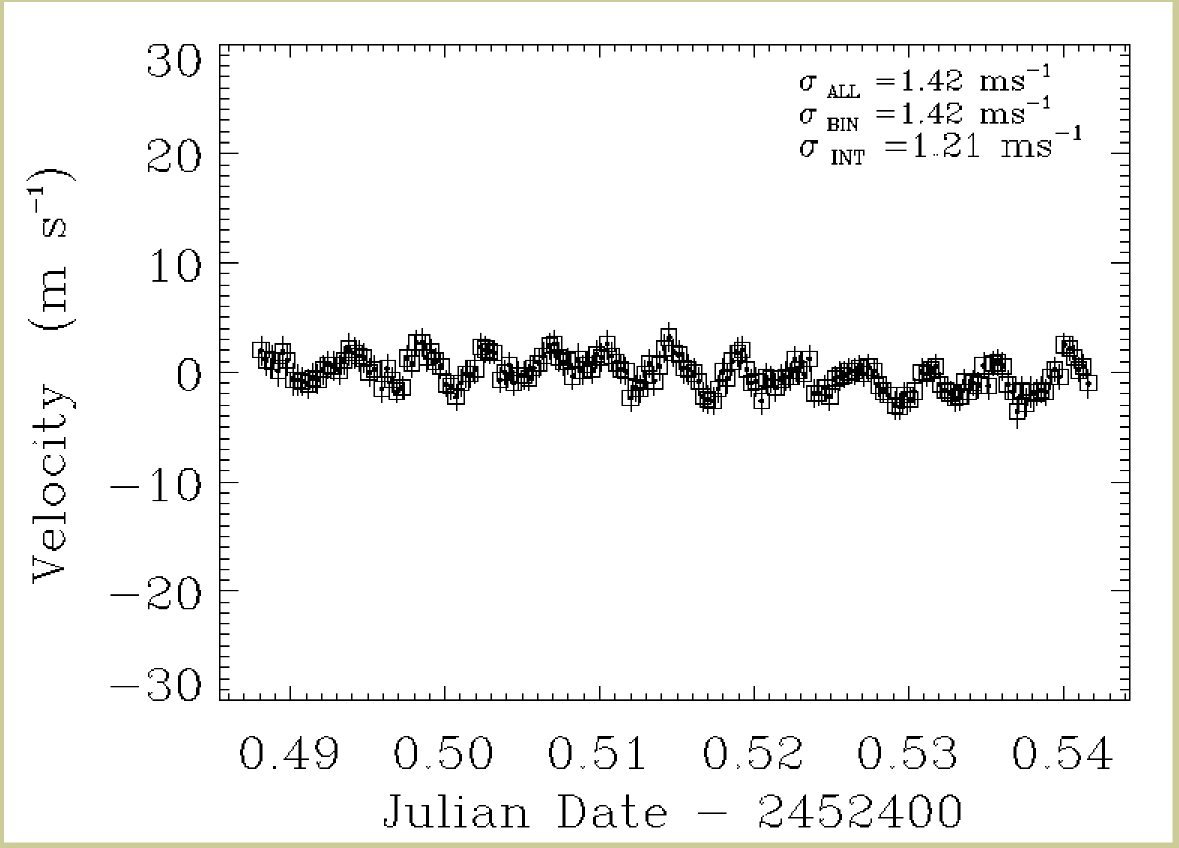
HIRES

new precision: 1m/s

- smaller pixels
- more wavelength coverage
- improved CCD controller electronics

With high enough sampling, this opens the possibility of detecting 10 M_Earth planets in close orbits

R. P. Butler: observations of αCen, a chromospherically inactive, old, slowly rotating, sunlike star



P-mode oscillations

5 minute periodicity, amplitude of about 3 m/s

Short exposure times would register snapshots of this RV variablility

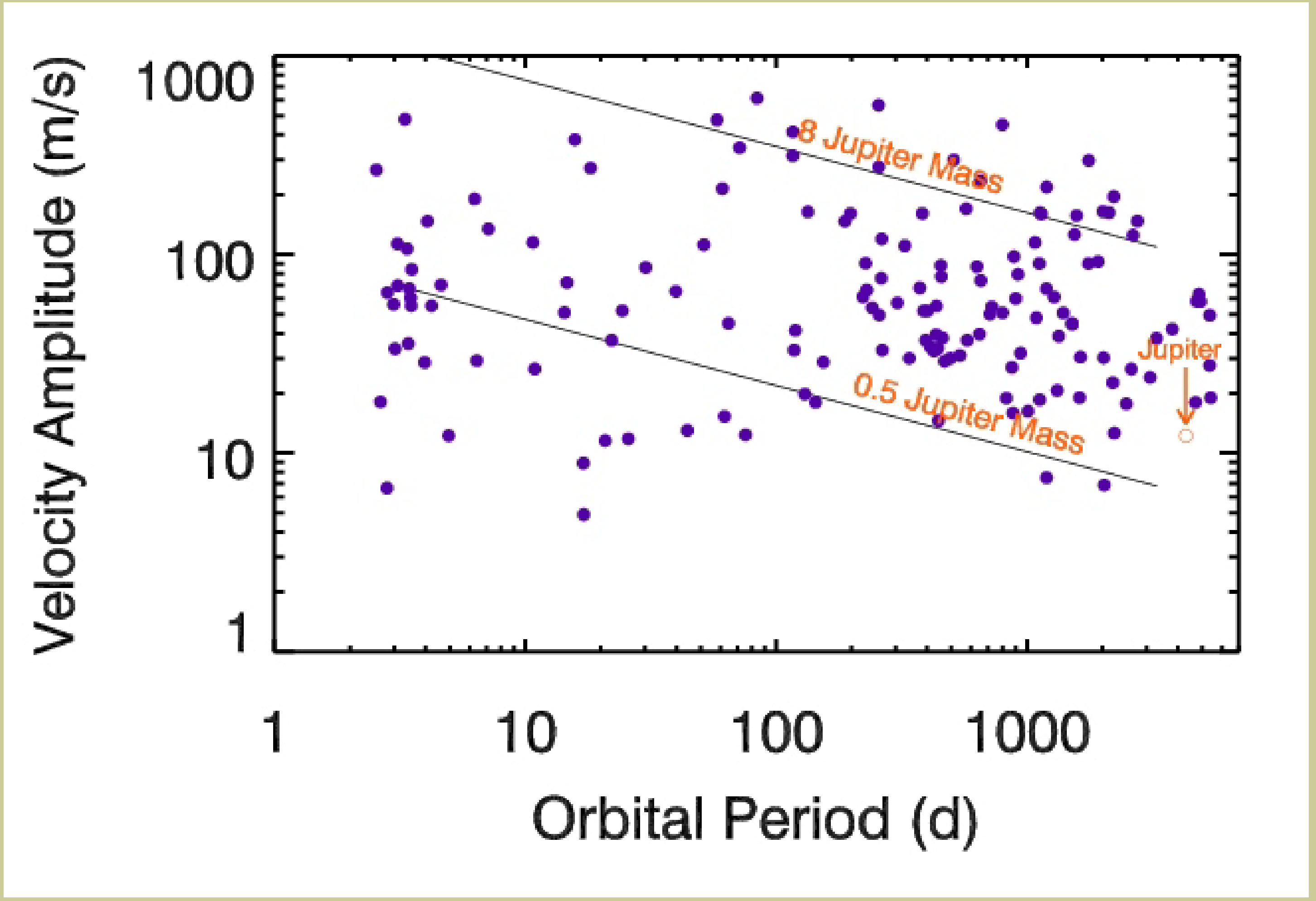
P-mode oscillations:

Millions of seismic eigenmodes driven by non-adiabatic granular pressure fluctuations are excited to low amplitudes with a frequency spectrum that grows as f^4 until it reaches a narrow maximum at 3 mHz, then drops off again toward higher frequencies.

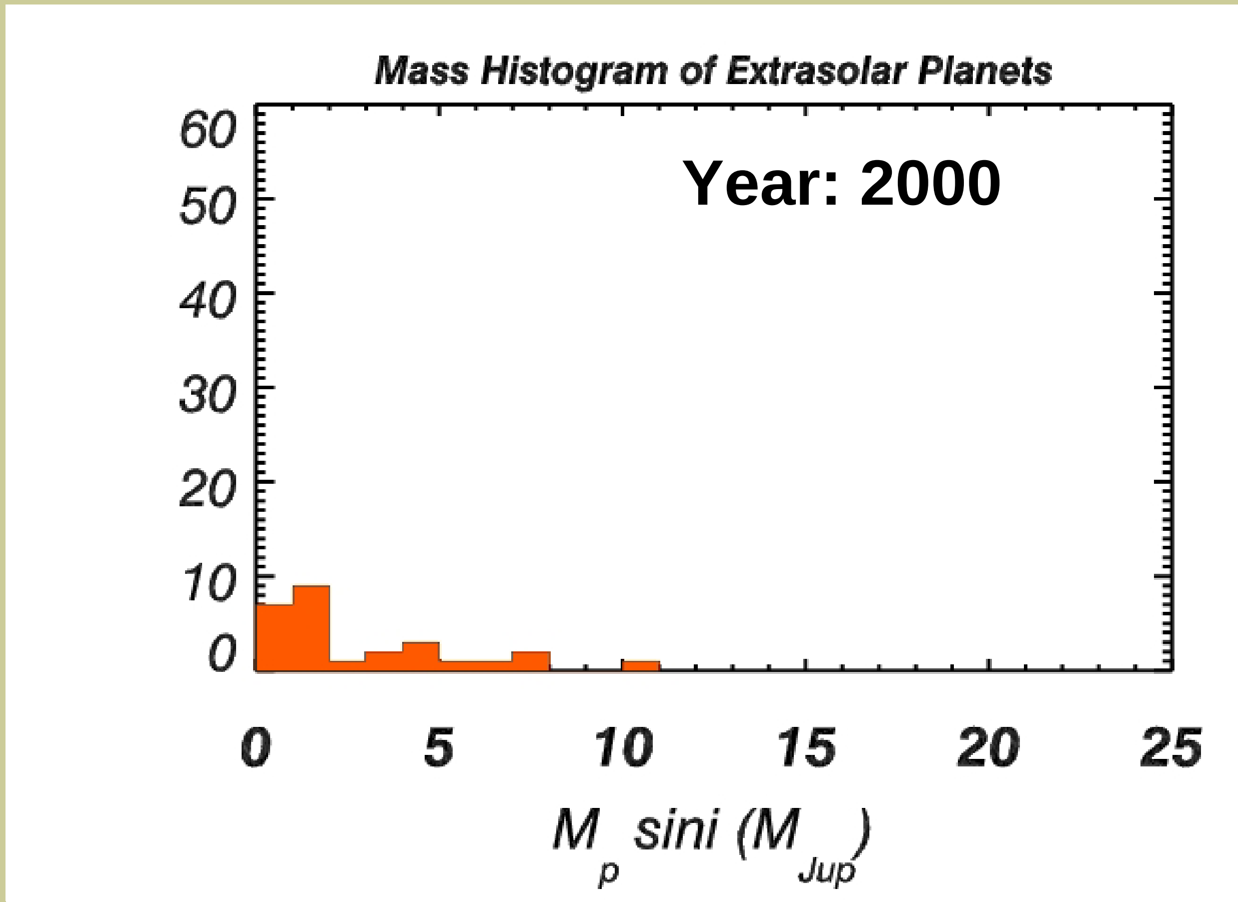
5 minute oscillations in the Sun.

Pressure modes move in and out of resonance - probably no way to correct for them. Instead, we average over them by taking longer or multiple exposures.

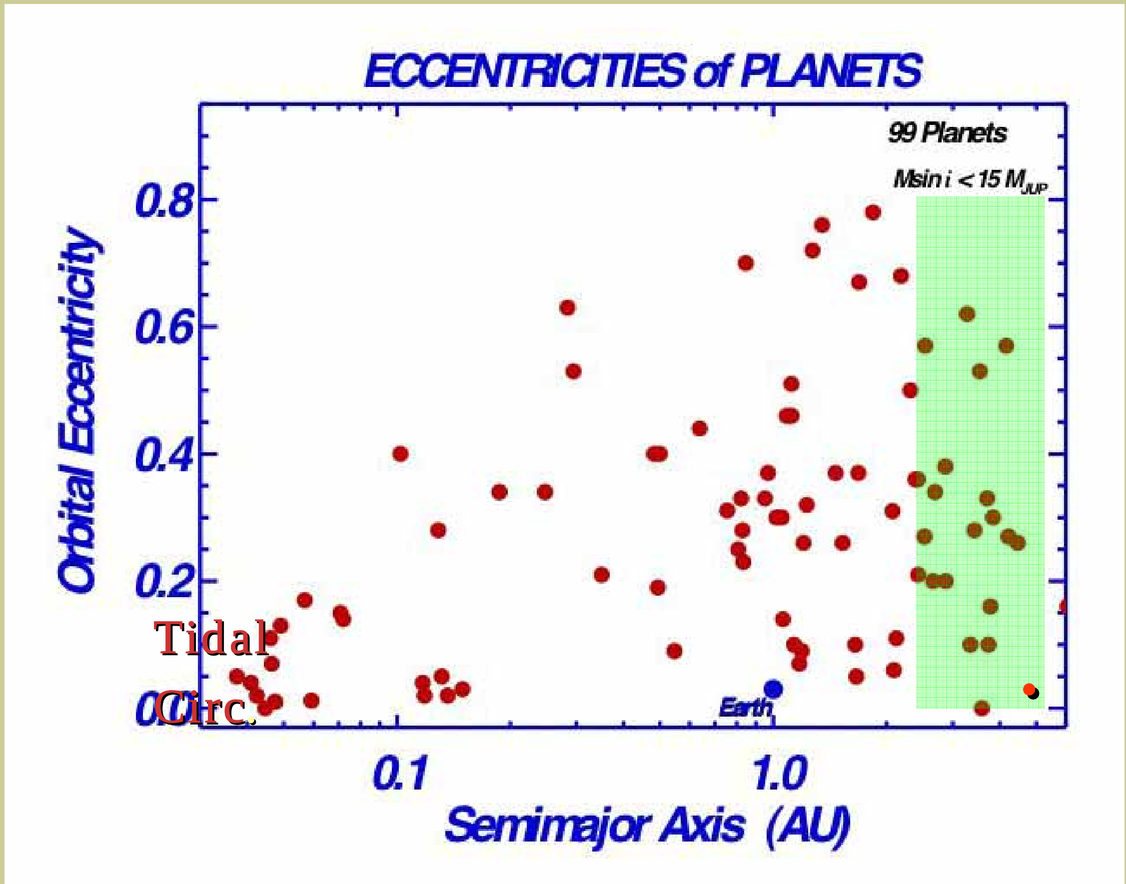
From the perspective of the Doppler technique, detectability is all about velocity precision, velocity amplitude and the length of time the star has been observed.



Mass Distribution and the Brown Dwarf Desert

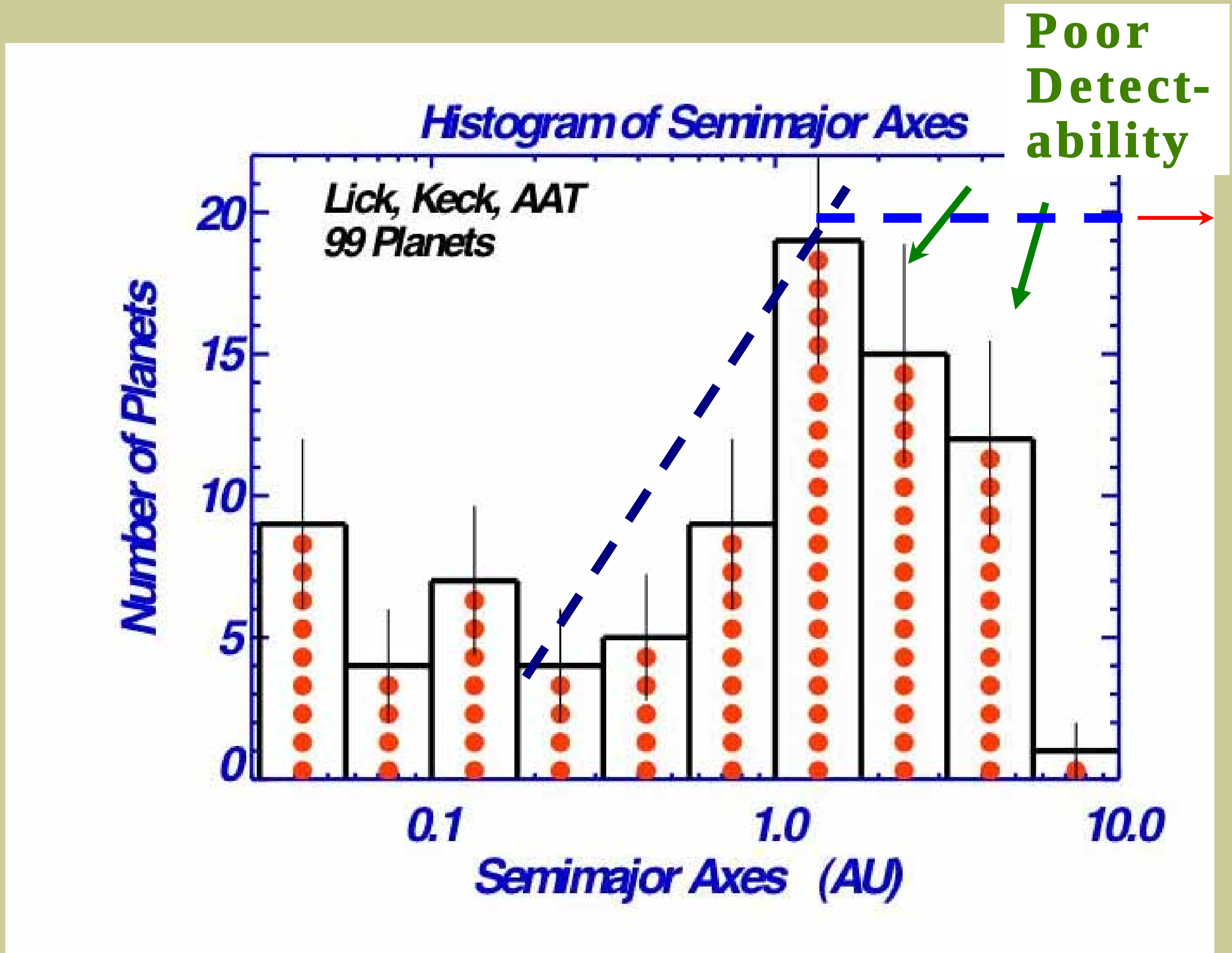


Orbital Eccentricities



Jupiters
at 2-4 AU:
Still
Eccentric

[See poster: Althea Moorhead on simulations to reproduce this observed distribution in ecc-arel parameter space]

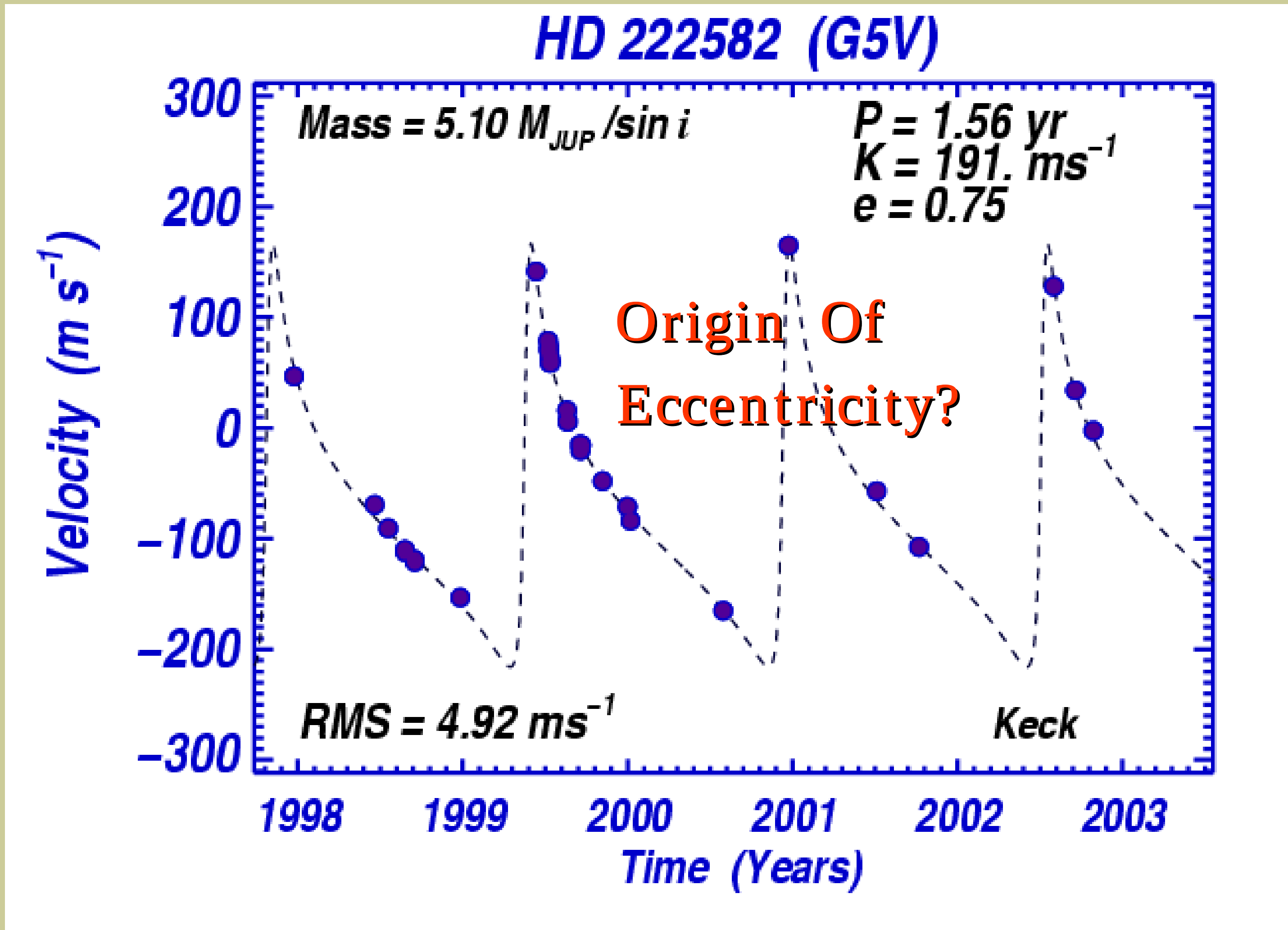


Flat Extrapolation:

+6% of stars have giant planets 3 - 20 AU .

Total: 12 %

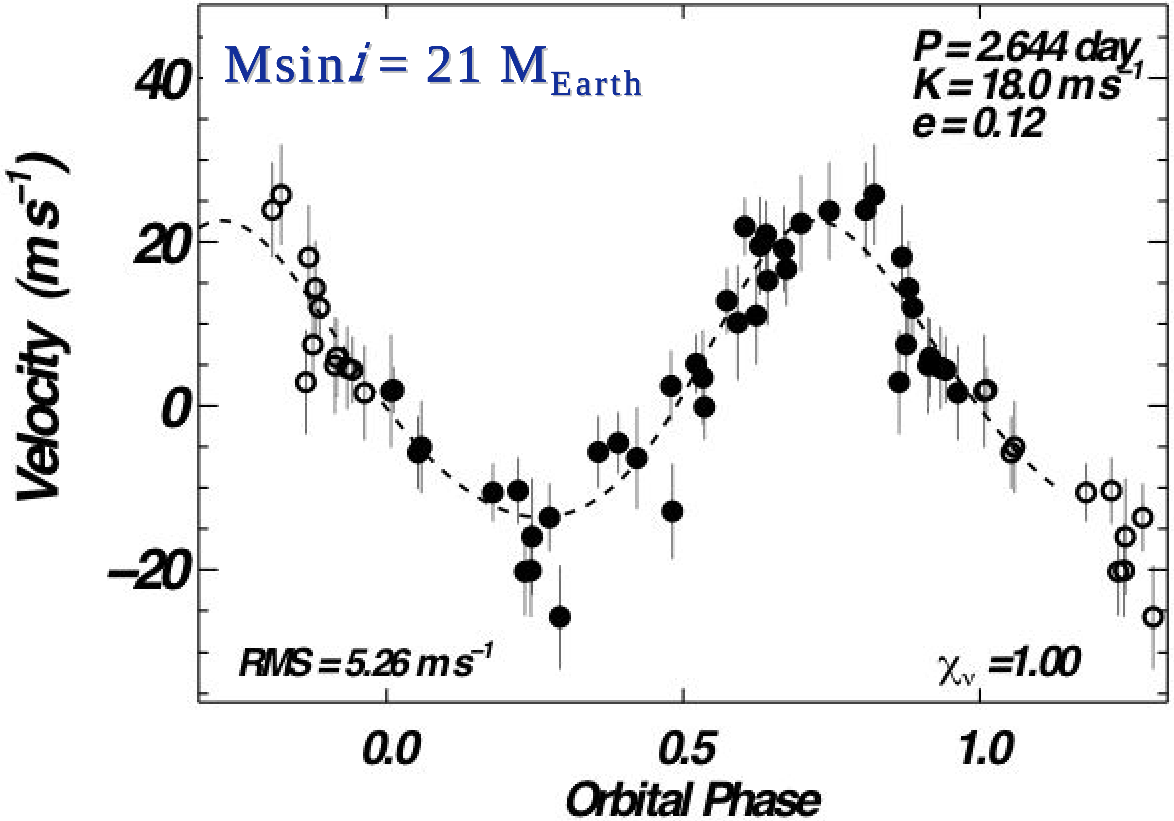
Planets in Eccentric Orbits



No Other Planets

Single Planet, Yet Eccentric.

Gliese 436:
Velocity vs. Phase



Tidal Lock

P = 2.64 d

Composition ?

- rock + ice
- rock + Fe
- gaseous

L = 1/50 L$_O$

Atmosphere?

- T$_{front}$ = 650 K
- T$_{back}$ < 200 K

Gliese 436:
Atmosphere & Thermal Coupling

Temp on Hot Hemisphere: 650 K

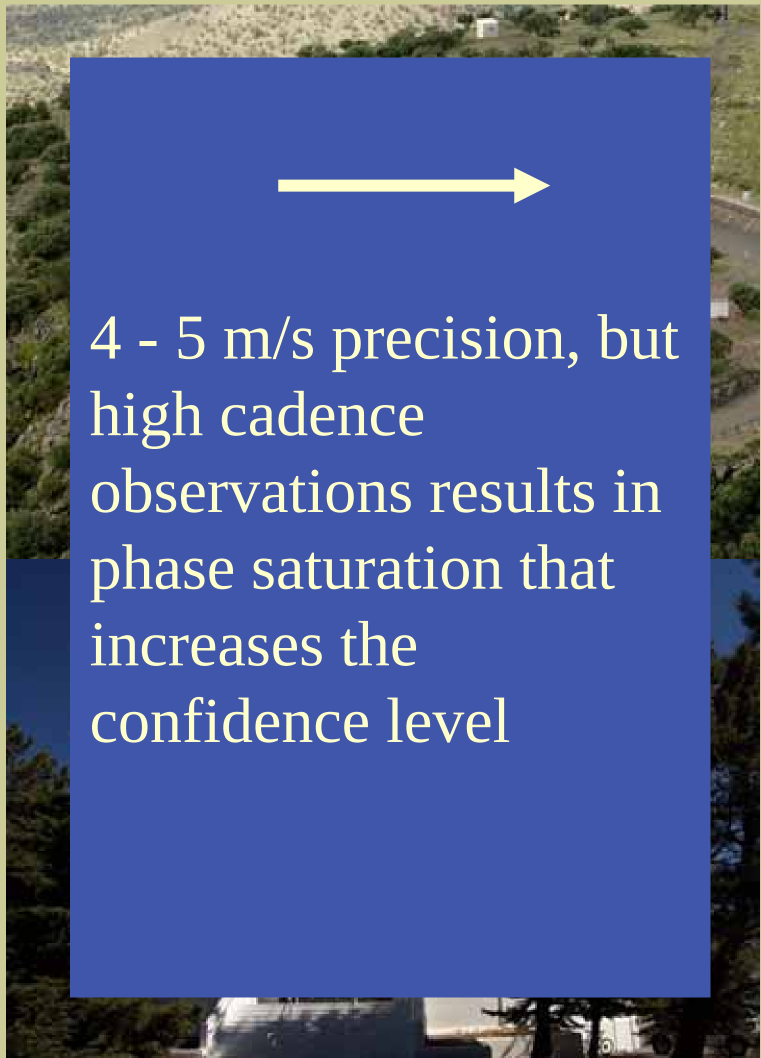
Questions:

- ***Retention of Atmos. & Envelope***
- ***Thermal coupling, front-to-back***
- ***Intermediate Temp ?***

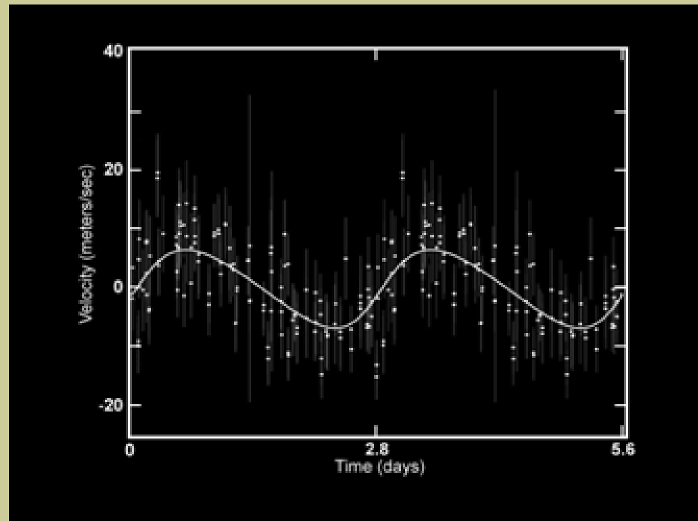
[See poster by M.F. Hattori: mass loss from close-in extrasolar giant planets]

HET and Lick:

4th planet orbiting 55 Cnc



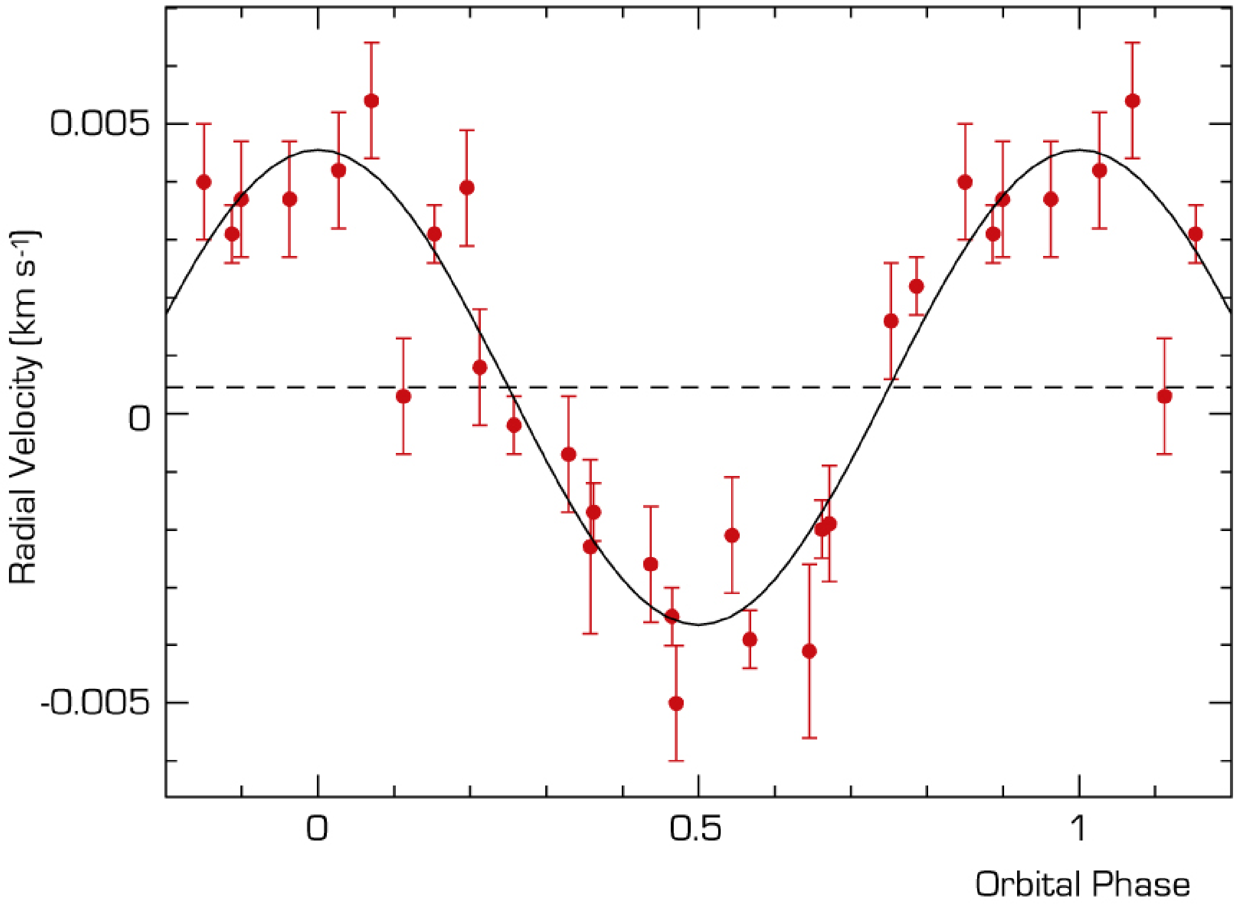
4 - 5 m/s precision, but high cadence observations results in phase saturation that increases the confidence level



QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

HARPS:

14 M_Earth planet around HD160691

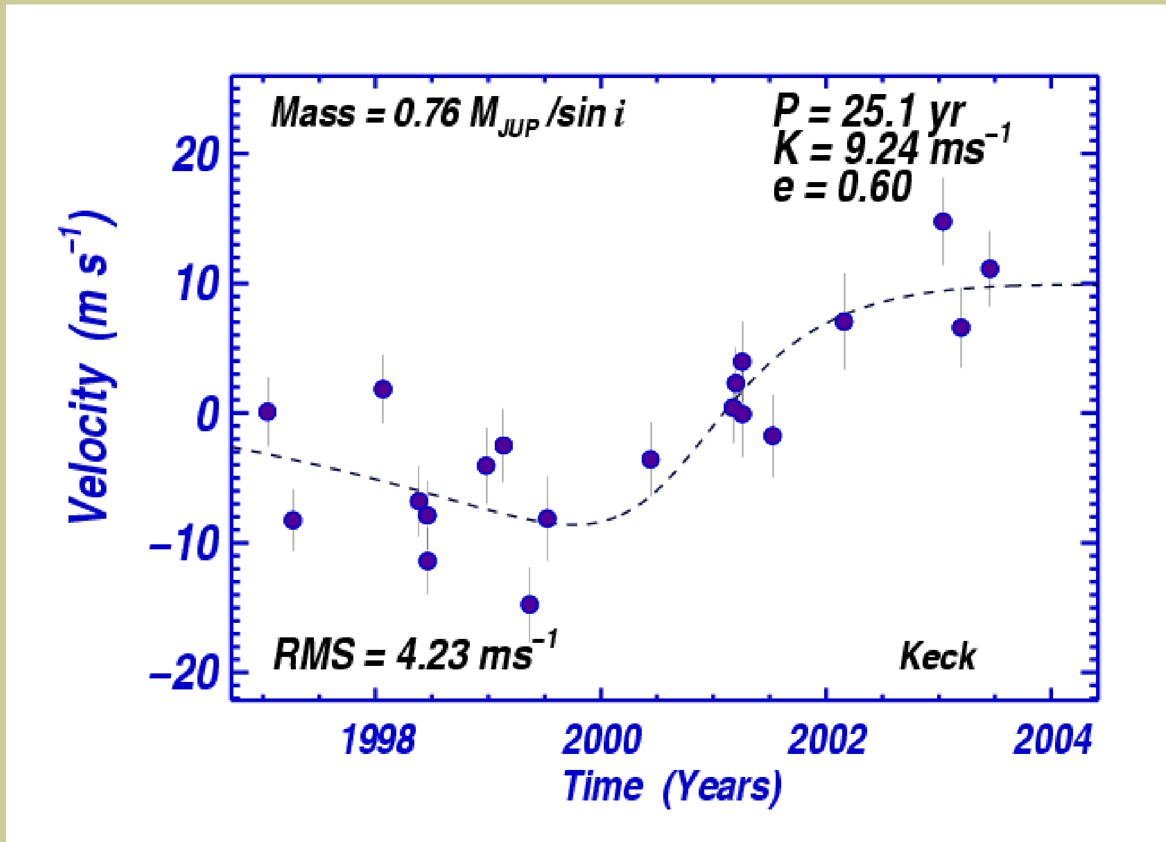


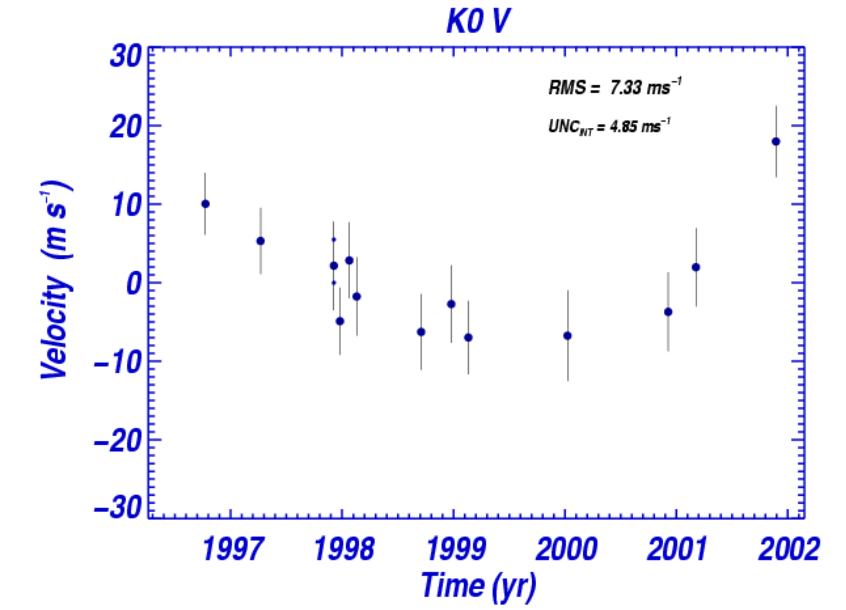
"Velocity Curve" of mu Arae

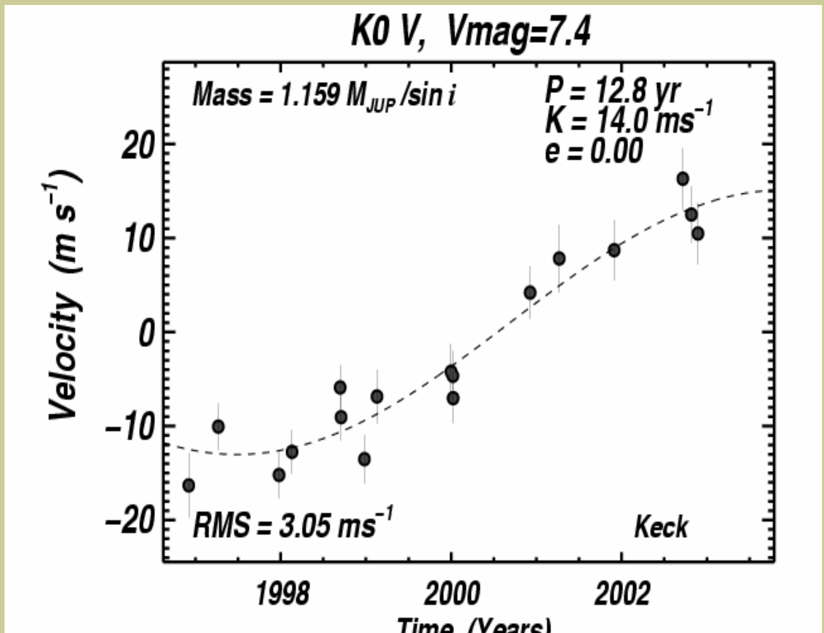
ESO PR Photo 25d/04 (25 August 2004)

Future: Planets Beyond 5 AU

G5 V







Jupiter Analogs?

Represents ~3 % of stars at Keck.

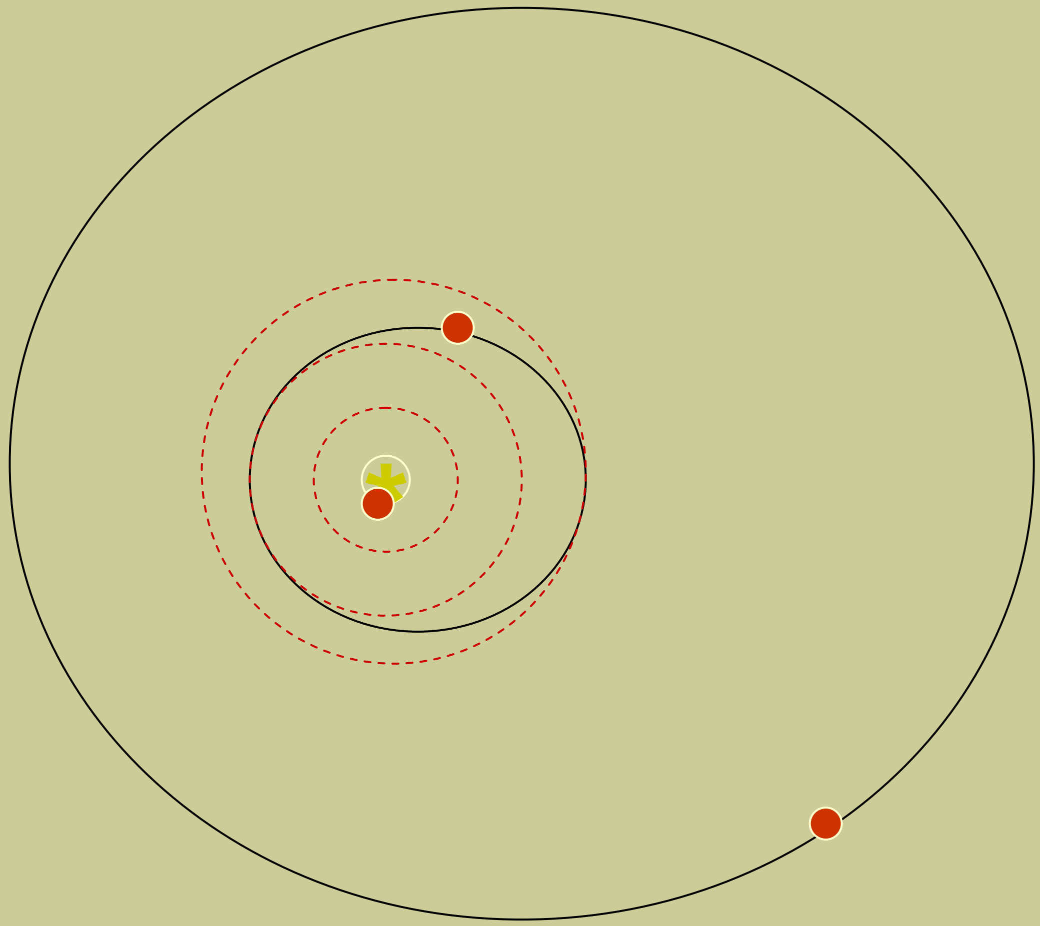
Orbits:

Circular or Eccentric?

Multiple planet systems are not just an odd curiosity

More than half of the systems we are finding appear to have more than one detectable planet!

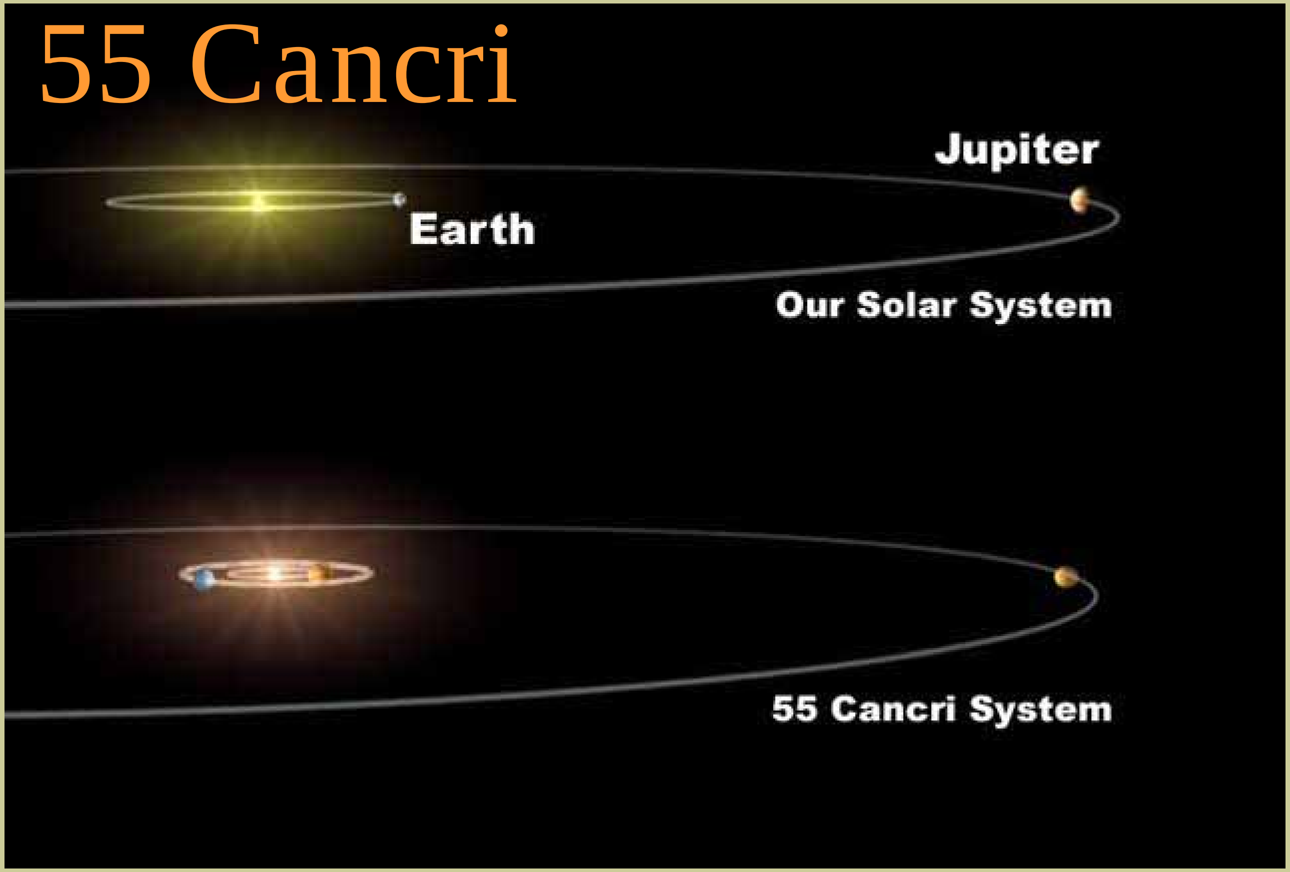
Upsilon Andromedae



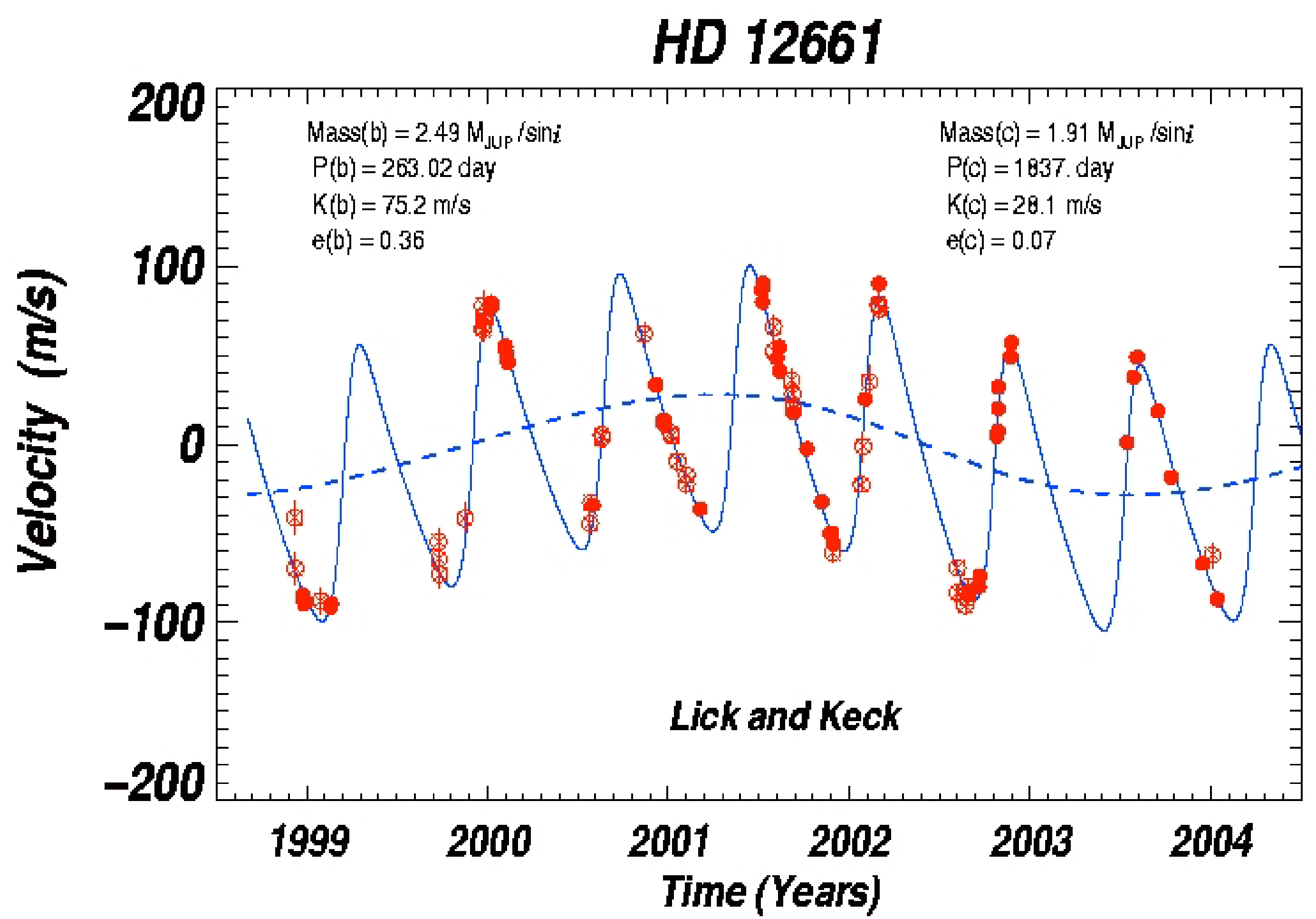
Stable planets in

Vast open spaces???

Lick Observatory



Lick Observatory



2.5 M_J

1.9 M_J

"Hierarchical" Double Planet

Weak Interactions

Possible 6:1 Resonance

Gozdziewski & Maciejewski,

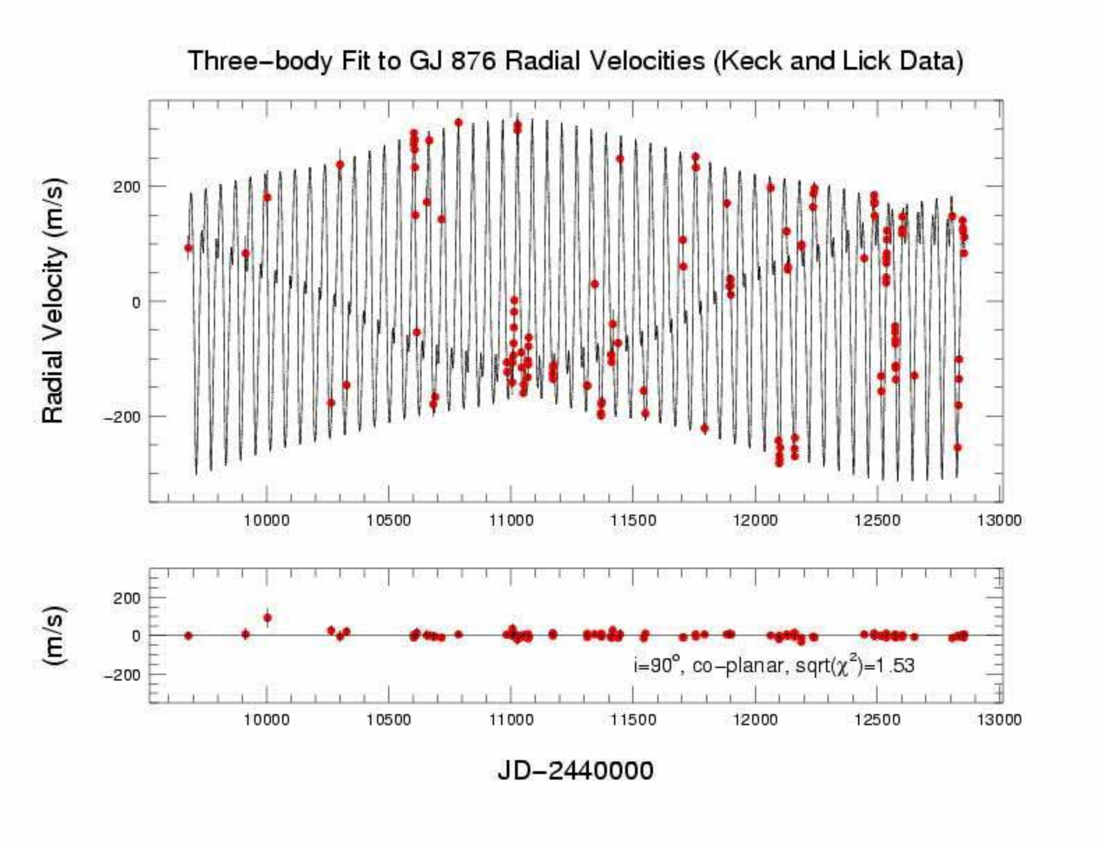
Lee & Peale

GL 876

2:1 Mean-Motion Resonance

&

Apsidal Lock

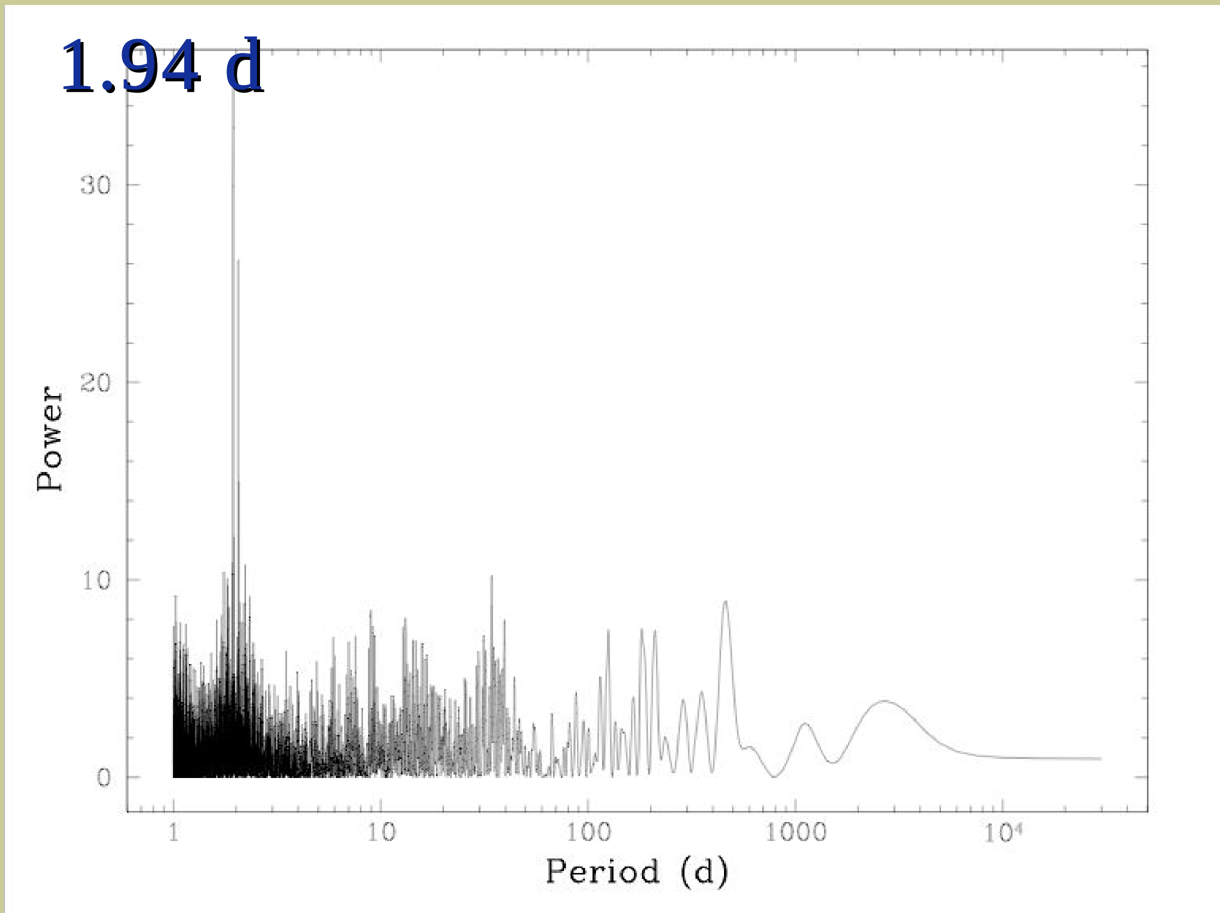


	Inner	Outer
P(d)	30.1	61.0
Msini	0.56	1.89 M_J
e	0.27	0.10
ω	330	333°

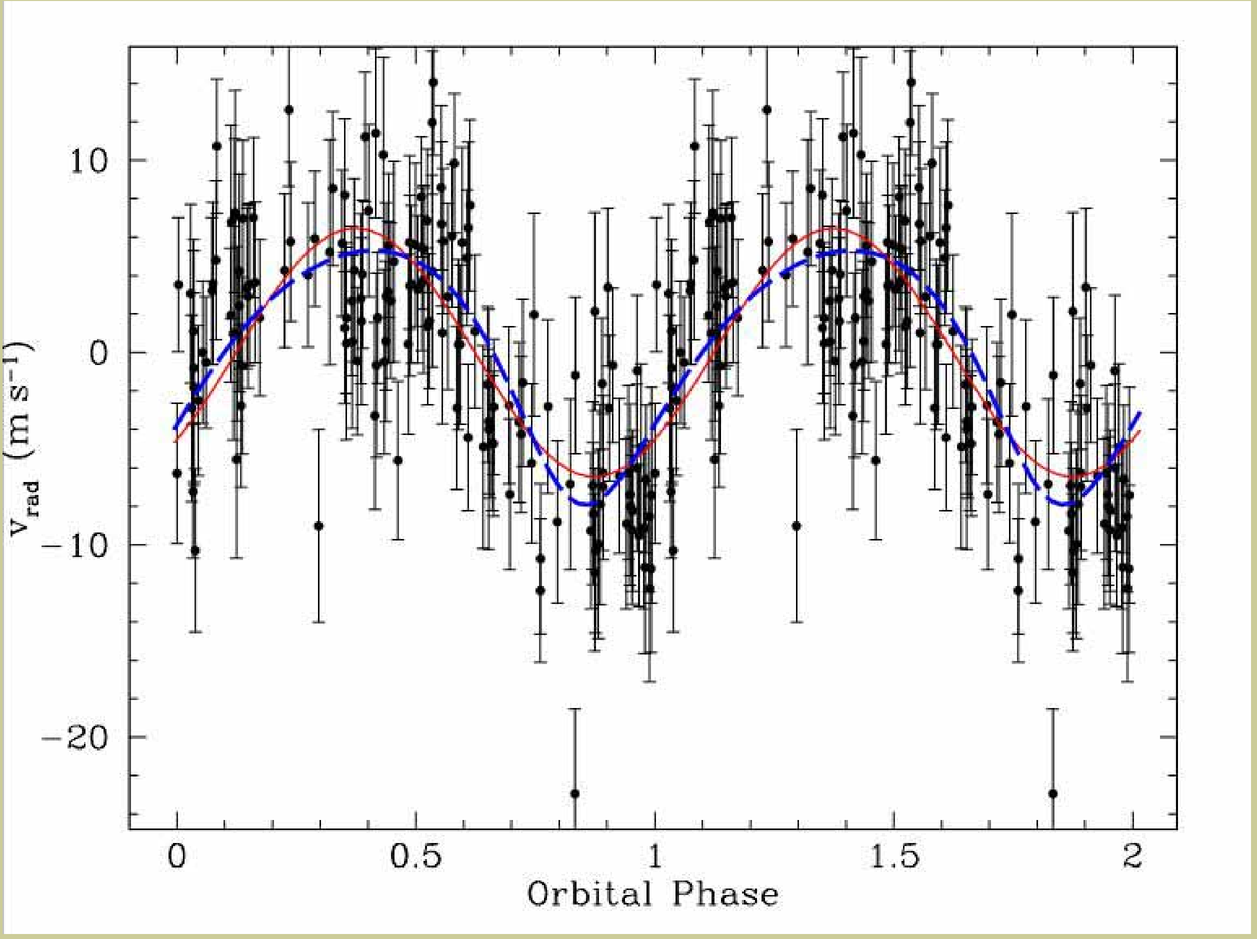
Resonance Theory:

- Laughlin & Chambers
- Lissauer & Rivera
- Man Hoi Lee & S.Peale

Periodogram of Residuals
to 2-Planet Fit



Fit to Residuals to 2-Planet fit



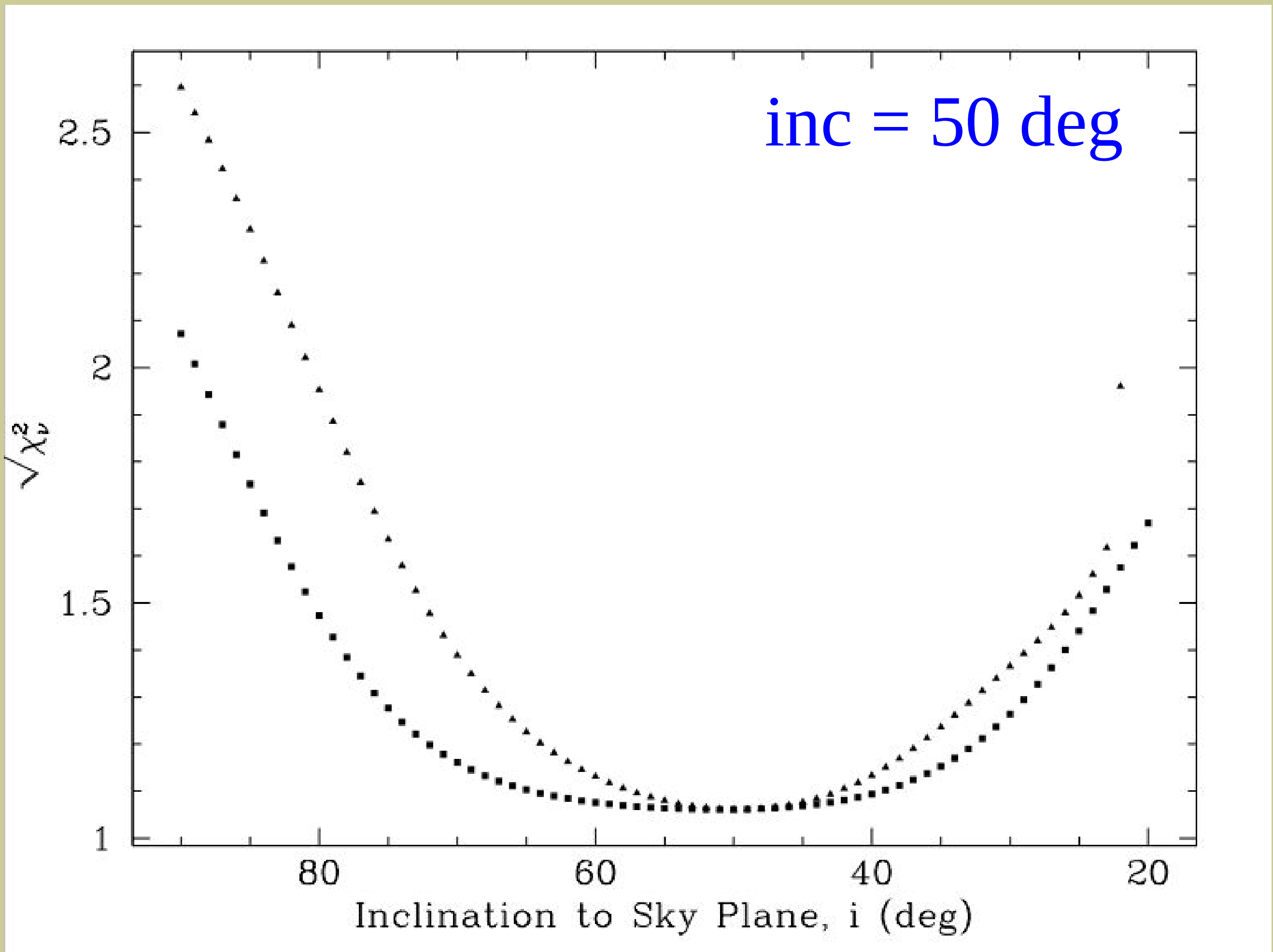
P = 1.94 d

Msini = 5.9 M_{earth}

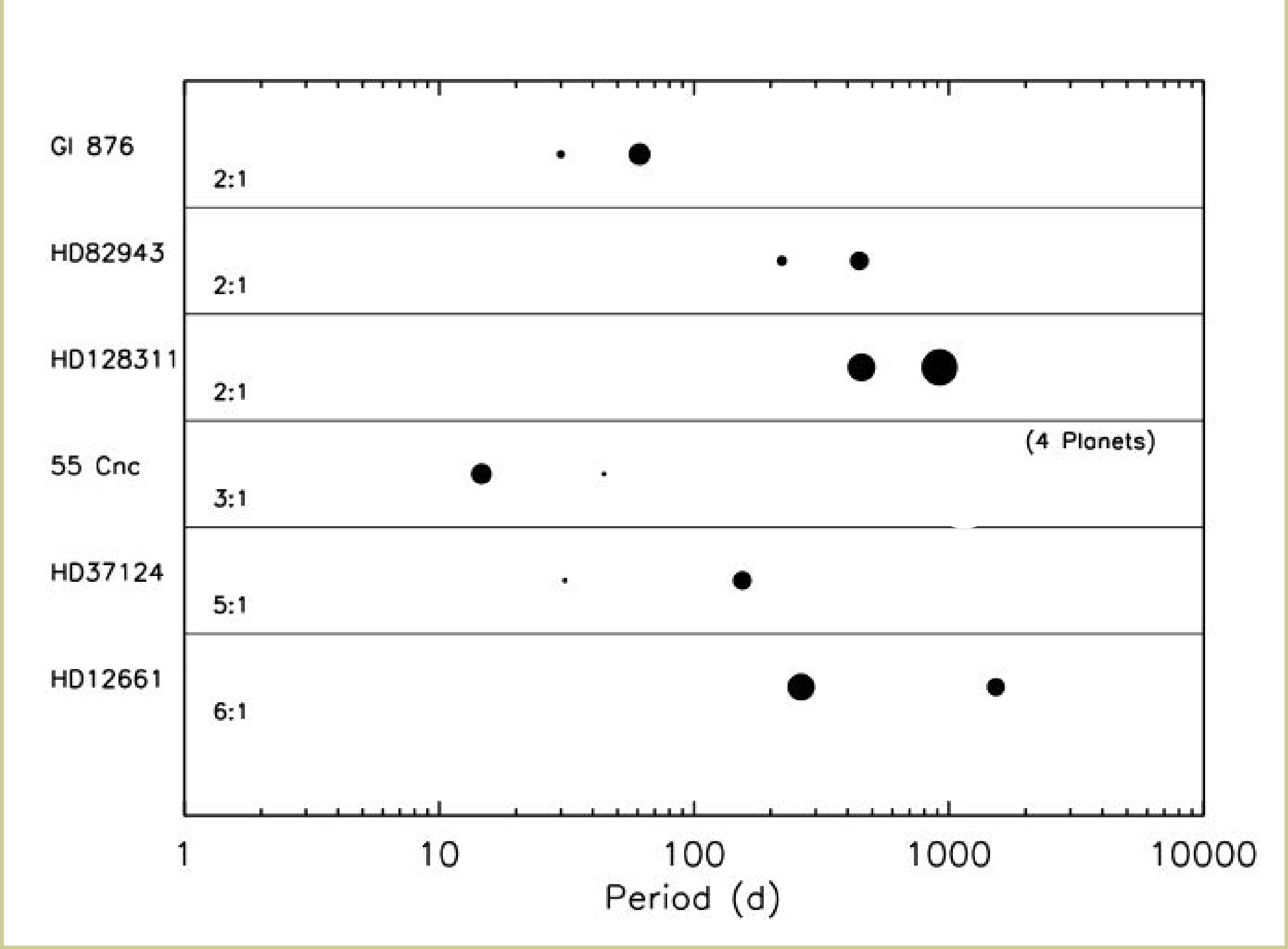
For i = 50 deg,

M_{pl} = 7.5 M_{Earth}

Inclination Constraint
from Planet-Planet Interaction



Exoplanetary Systems in Resonances



COFFEE BREAK

(20 minutes)

Planet-Metallicity Correlation

Stars with detected extrasolar planets are metal-rich

Accretion?

Lin, Bodenheimer & Richardson (1996), Gonzalez (1997/9, 2000)

Laughlin & Adams (1997), Sandquist et al. (1998)

Murray et al. (2001), Fuhrmann, Pfeiffer & Bernkopf (1997/8)

Israelian et al., 2002, Santos et al. (2000, 2003, 2004),

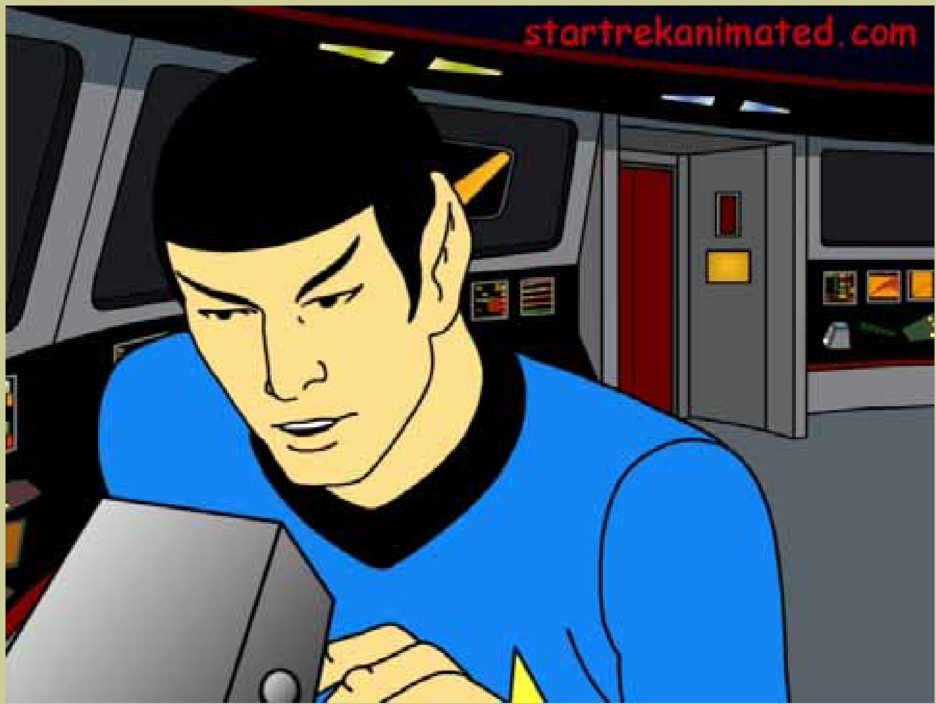
Sadakane et al. (2002), Laws et al. (2003)

Initial Condition?

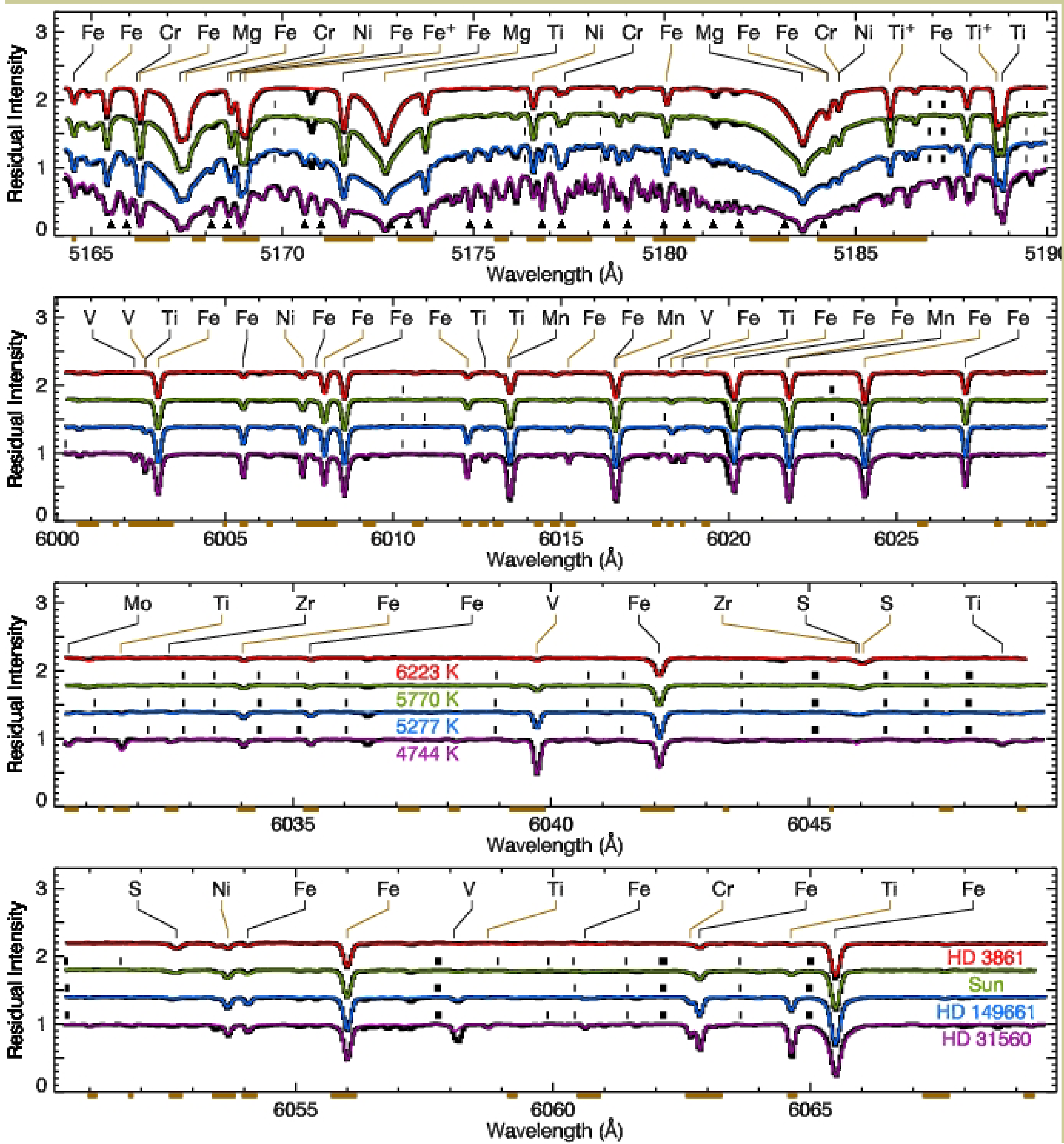
Pinsonneault, DePoy, Coffee (2001)

Spectral Parameters Of Cool Stars (SPOCS I.)

- with Jeff Valenti, STScI



Catalog of 1040 FGK stars from Lick, Keck, AAT

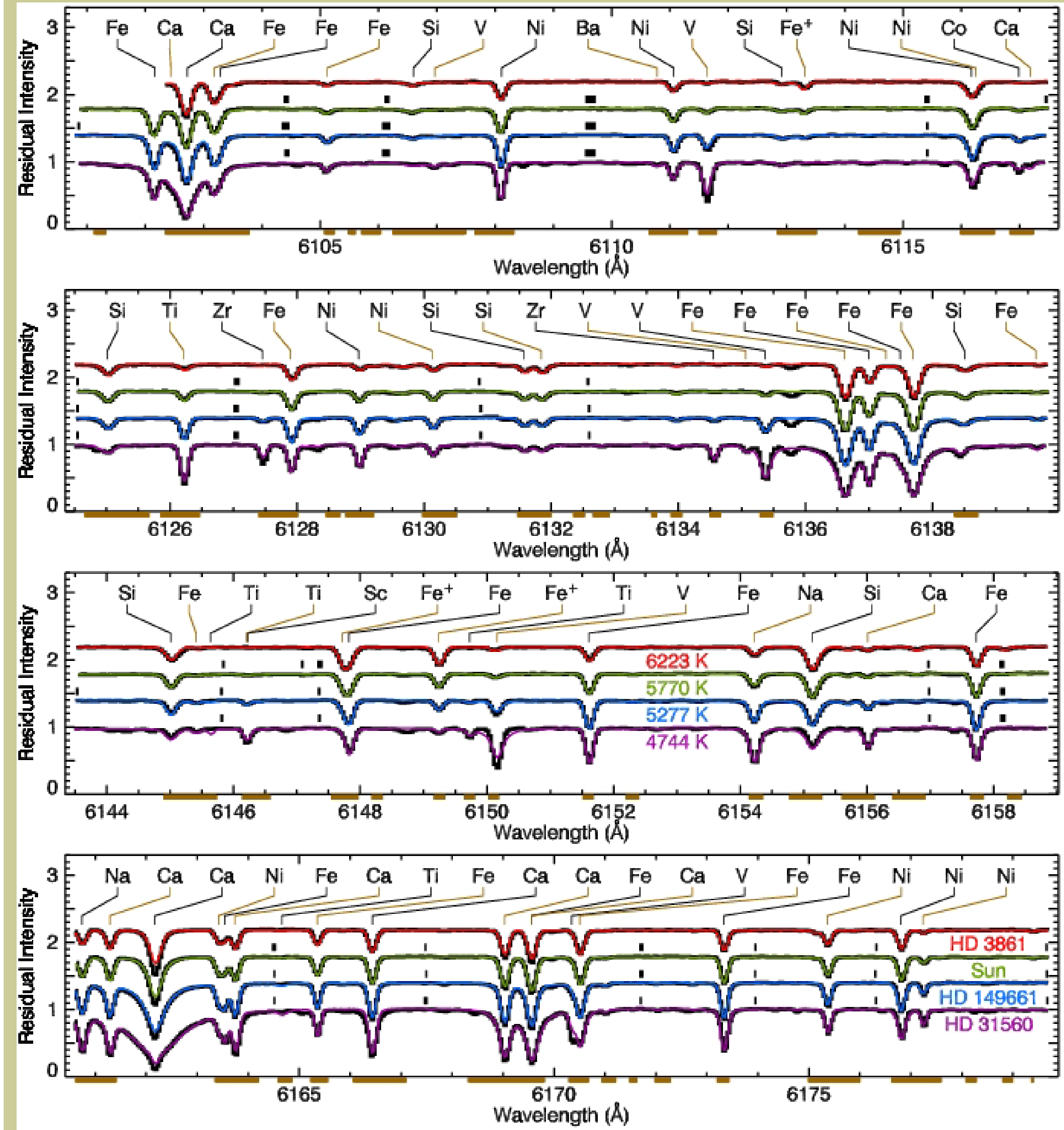


Spectral Synthesis Modeling (SME)

1) First use NSO atlas to tune log gf values, broadening coefficients, wavelengths.

2) Assume LTE, drive a radiative transfer code with Kurucz model atmospheres.

3) Marquardt fit to continuum and spectral lines in selected wavelength segments.



Spectral Synthesis Modeling (SME)

Several hundred neutral and ionized atomic lines.

More than 300 molecular lines (MgH and C2).

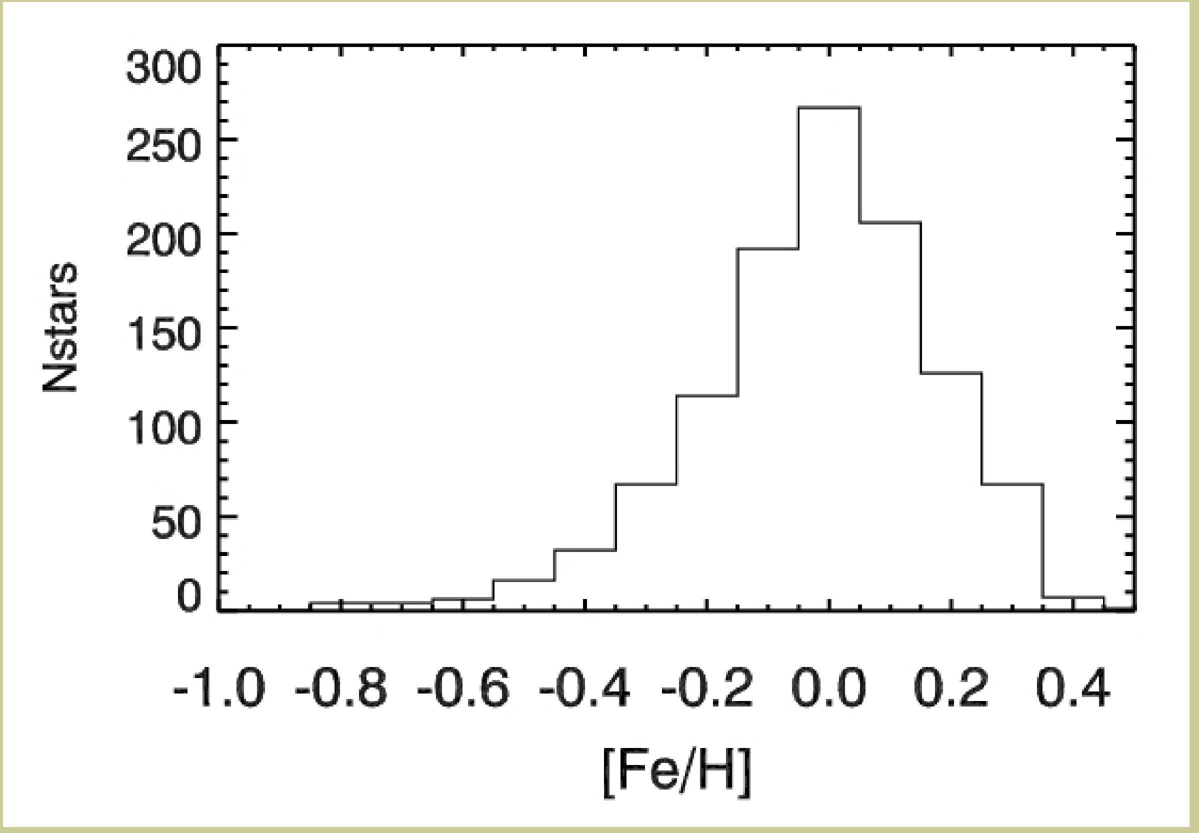
Free parameters: Teff, [M/H], log g, vsini, [Fe/H], [Si/H], [Na/H], [Ti/H], [Ni/H]

[See poster by Genya Takeda: New stellar evolution models using this data set]

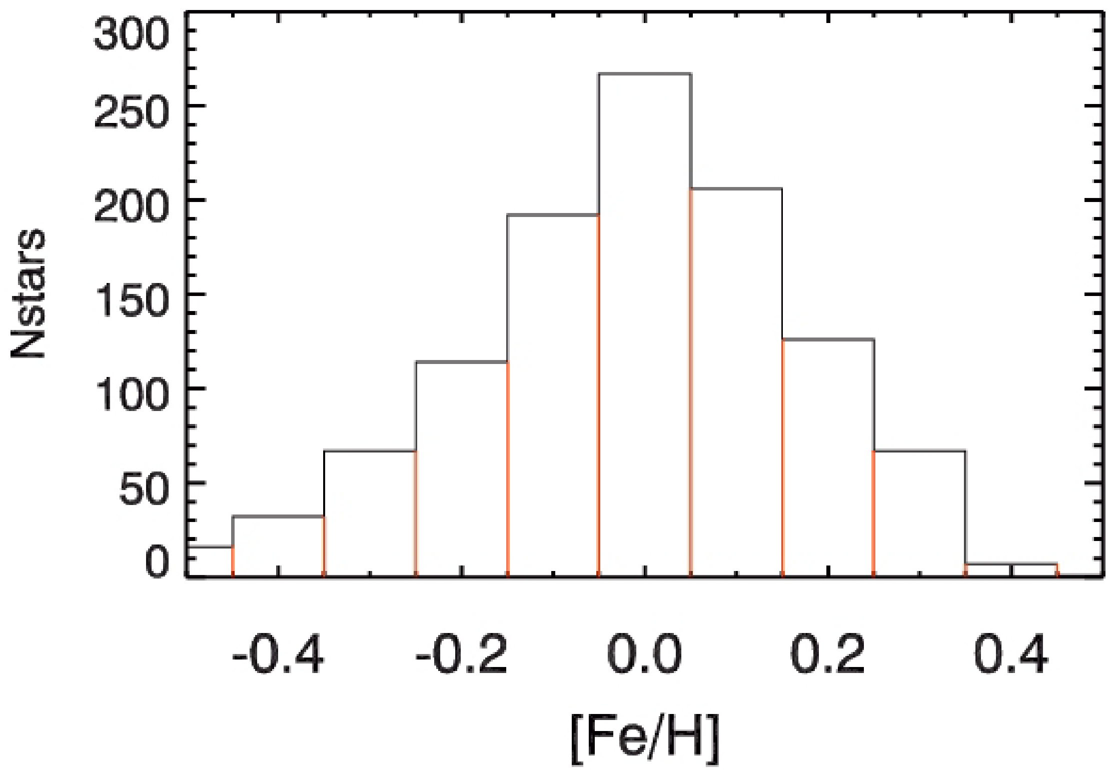
Analyzed 1900 spectra for 1040 stars

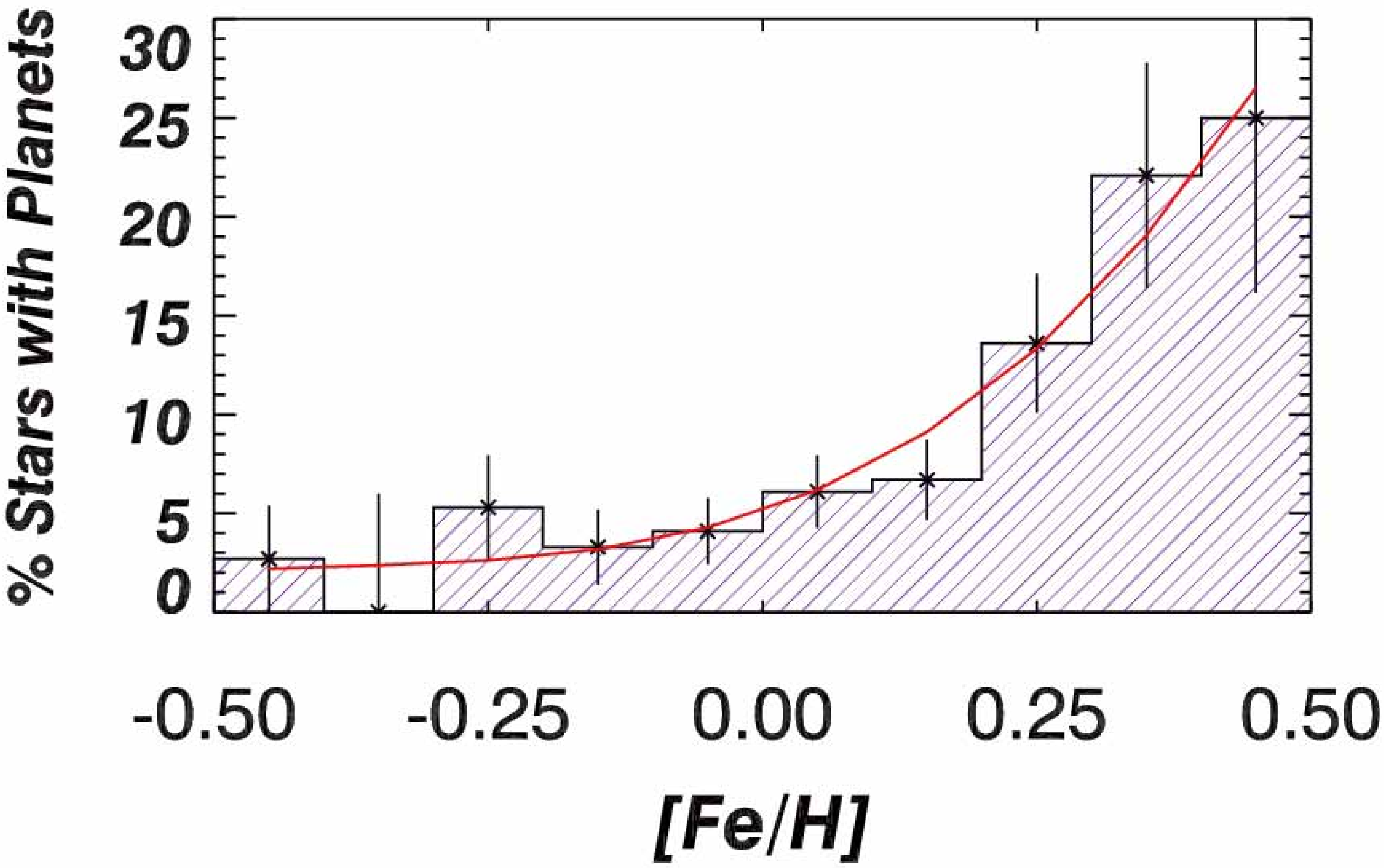
Not all stars have uniform detectability for planets, so restricted the sample to 964 stars where these planets could have been detected.

Binned the stars by metallicity and asked what fraction of stars in each metallicity bin have planets with Msini > 0.5 M_Jup and orbital periods shorter than 3 years.



300
250
200
150
100
50
0
Nstars
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
[Fe/H]


300
250
200
150
100
50
0
Nstars
-0.4
-0.2
0.0
0.2
0.4
[Fe/H]


% Stars with Planets
30
25
20
15
10
5
0
-0.50
-0.25
0.00
0.25
0.50
[Fe/H]

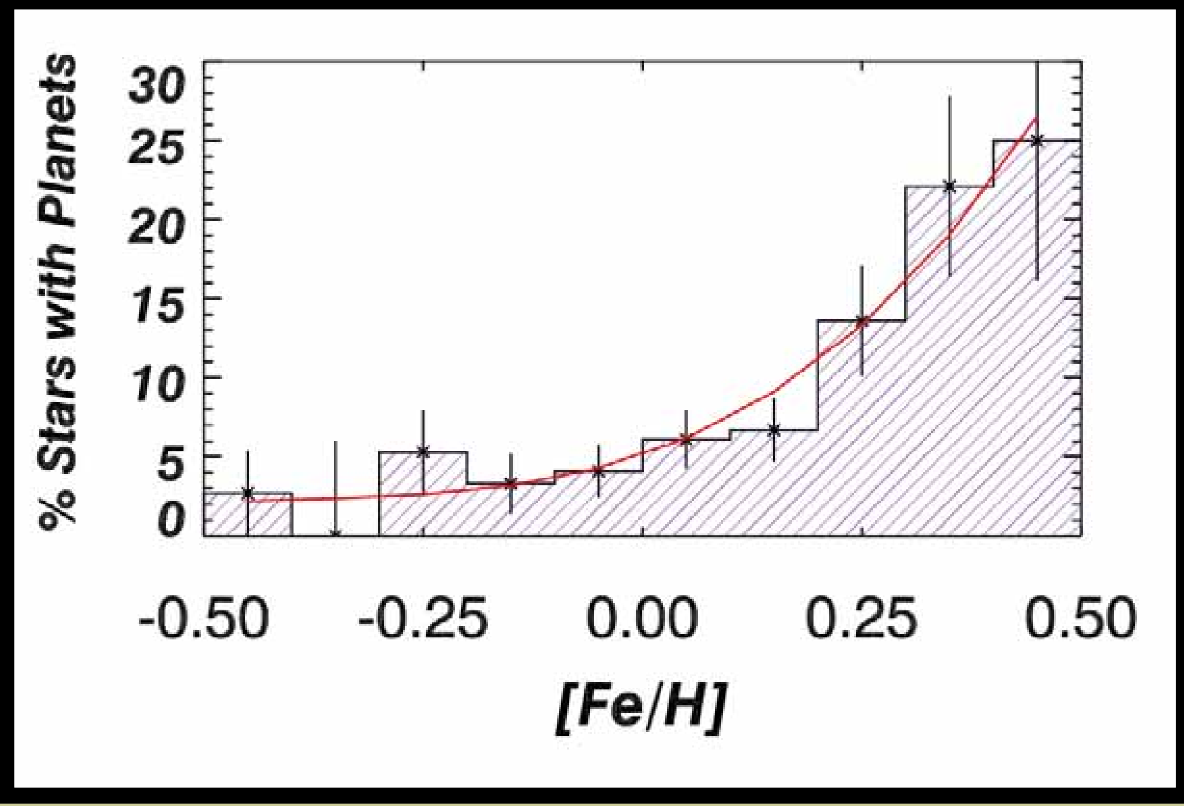
$$P(\text{planet}) = 0.05 \times 10^{2.0 \times [Fe/H]}$$

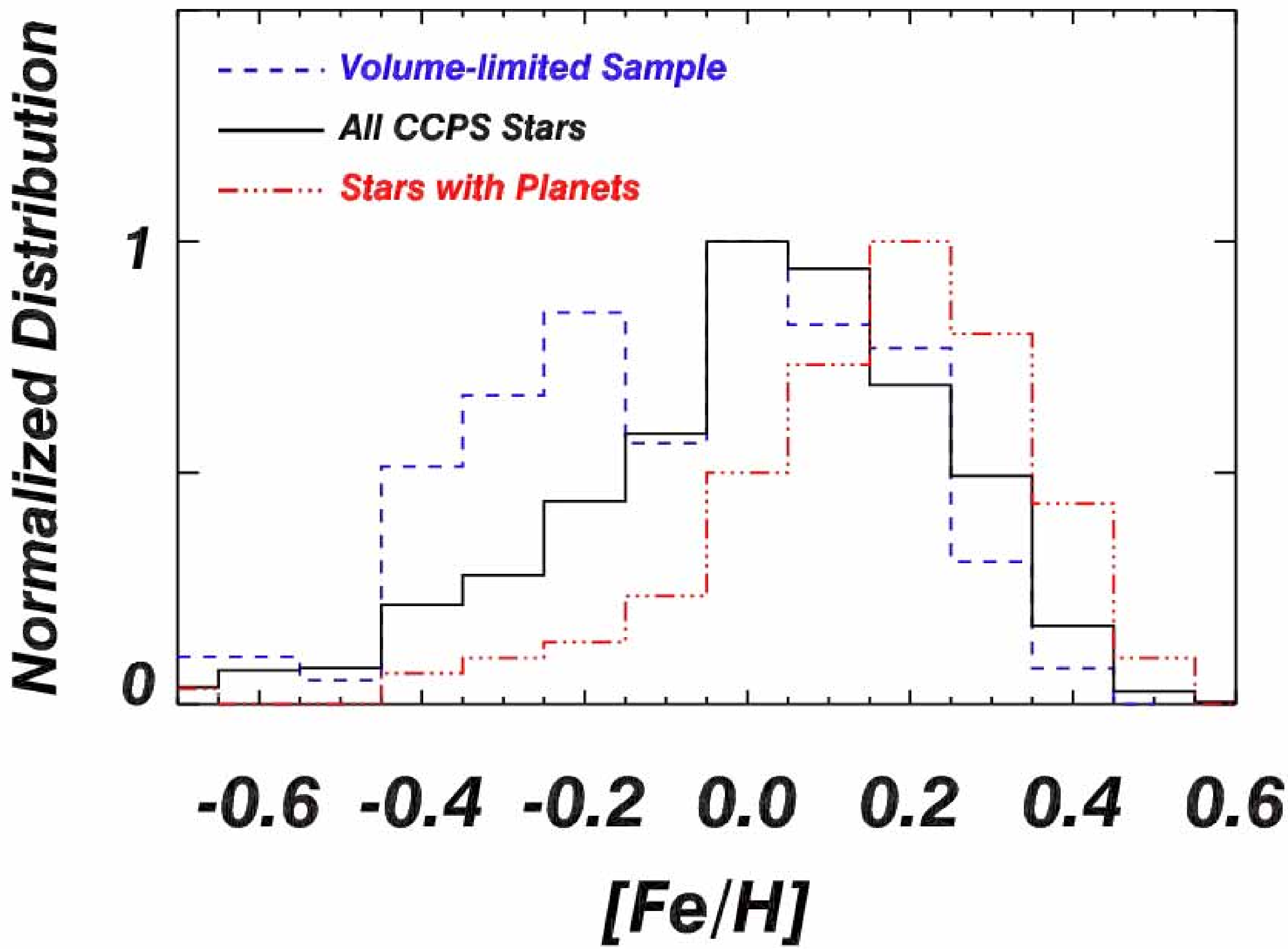
$$[Fe/H] = \log(N_{Fe}/N_H) - \log(N_{Fe}/N_H)_{SUN}$$

$$P(\text{planet}) = 0.05 \times \left(\frac{(N_{Fe}/N_H)}{(N_{Fe}/N_H)_{SUN}} \right)^{2.0}$$

Probability of forming a gas giant planet is a power law that goes approximately as the square of the number of metal atoms.

$$P(\text{planet}) = 0.05 \times \left(\frac{(N_{Fe}/N_H)}{(N_{Fe}/N_H)_{SUN}} \right)^{2.0}$$





Volume-limited Sample
All CCPS Stars
Stars with Planets
Normalized Distribution
1
0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
[Fe/H]

The occurrence of gas giant planets is a sensitive function of metallicity

- < 5% of stars with [Fe/H] < 0.0 have gas giant planets

- ~ 25% of stars with [Fe/H] > 0.3 have gas giant planets

- Probability of forming a gas giant planet is a power law, proportional to (approx) the square of the number of metal atoms

- particle collision rates similarly proportional to the square of the number of particles.

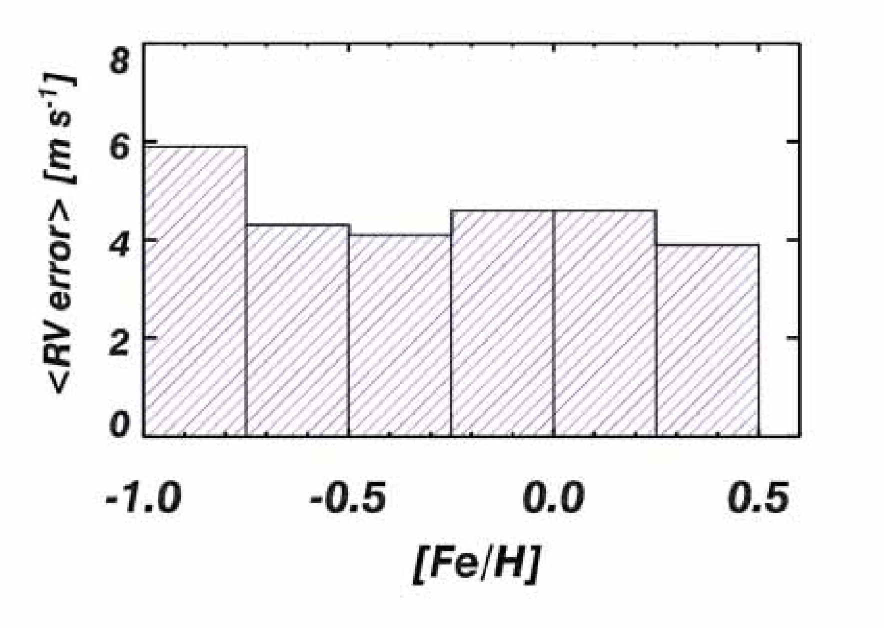
A Link between particle collision rates and the formation of gas giant planets?

Metal Poor Stars

Latham & Sozzeti Survey

Mayor et al HARPS survey

No Detections!



No observational bias against detection of planets around stars with:

-0.5 > [Fe/H] > -1.0

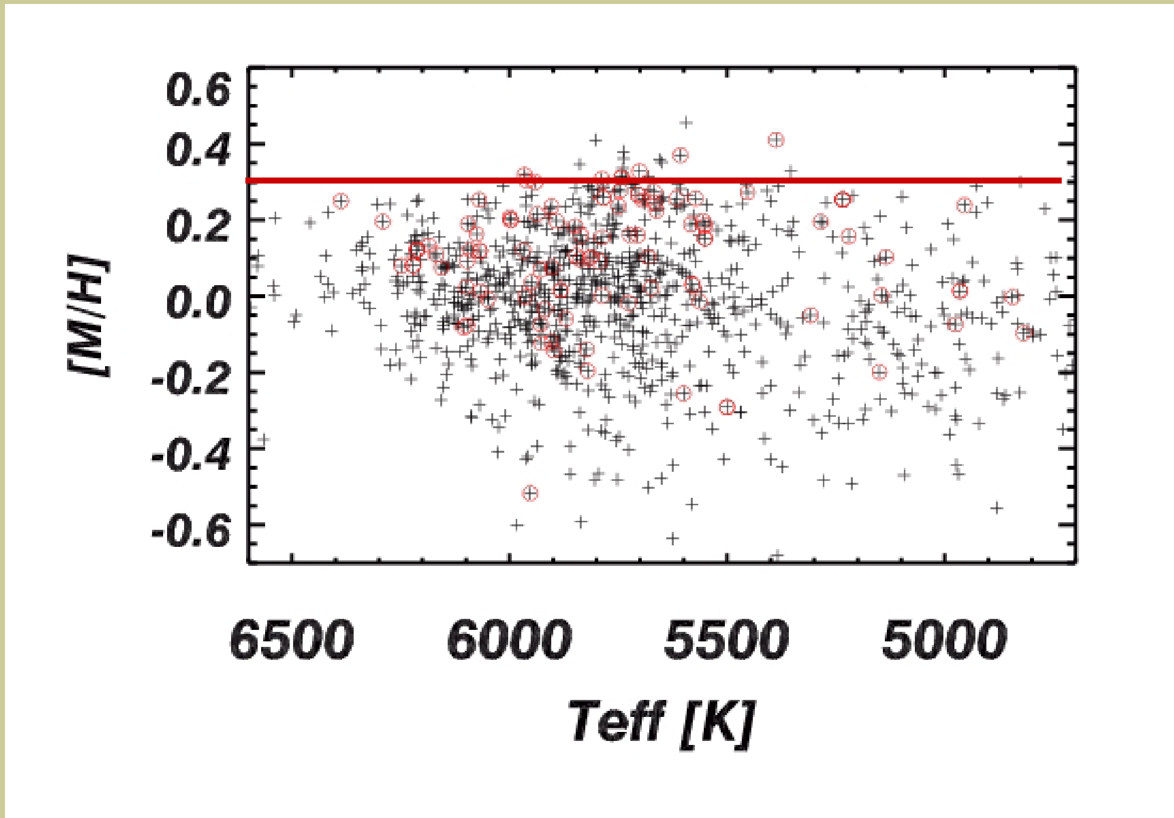
If accretion, then…

Expect difference in maximum observed abundances for F- and later-type stars

F stars, thin CZ

late G stars, thick CZ

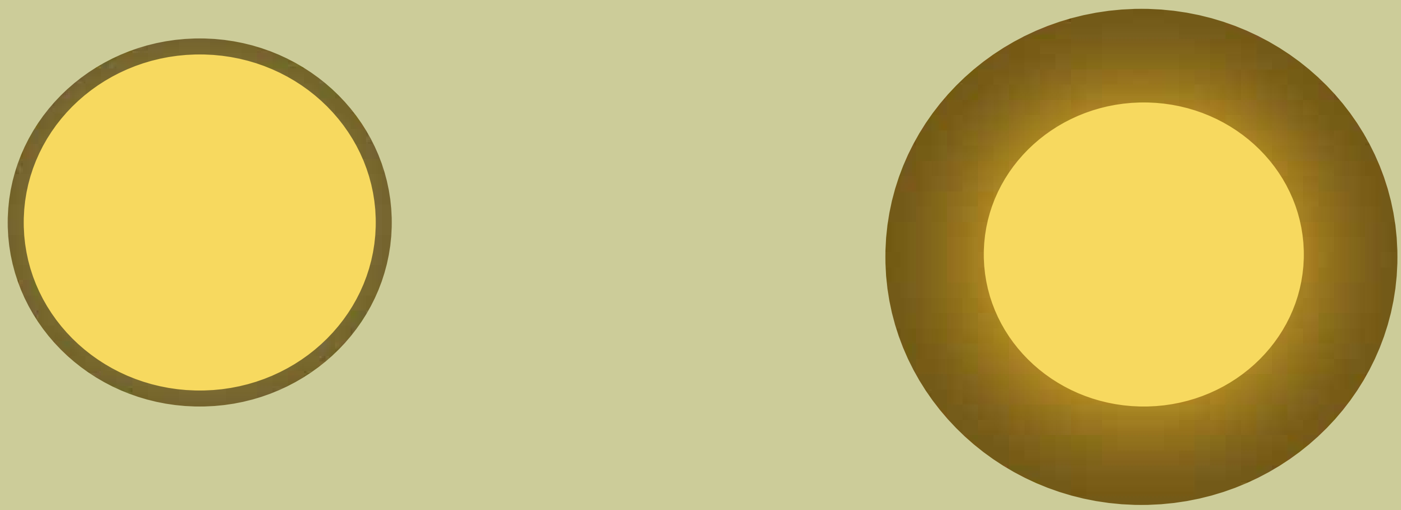
No rise in upper envelope metallicity for earlier type stars!

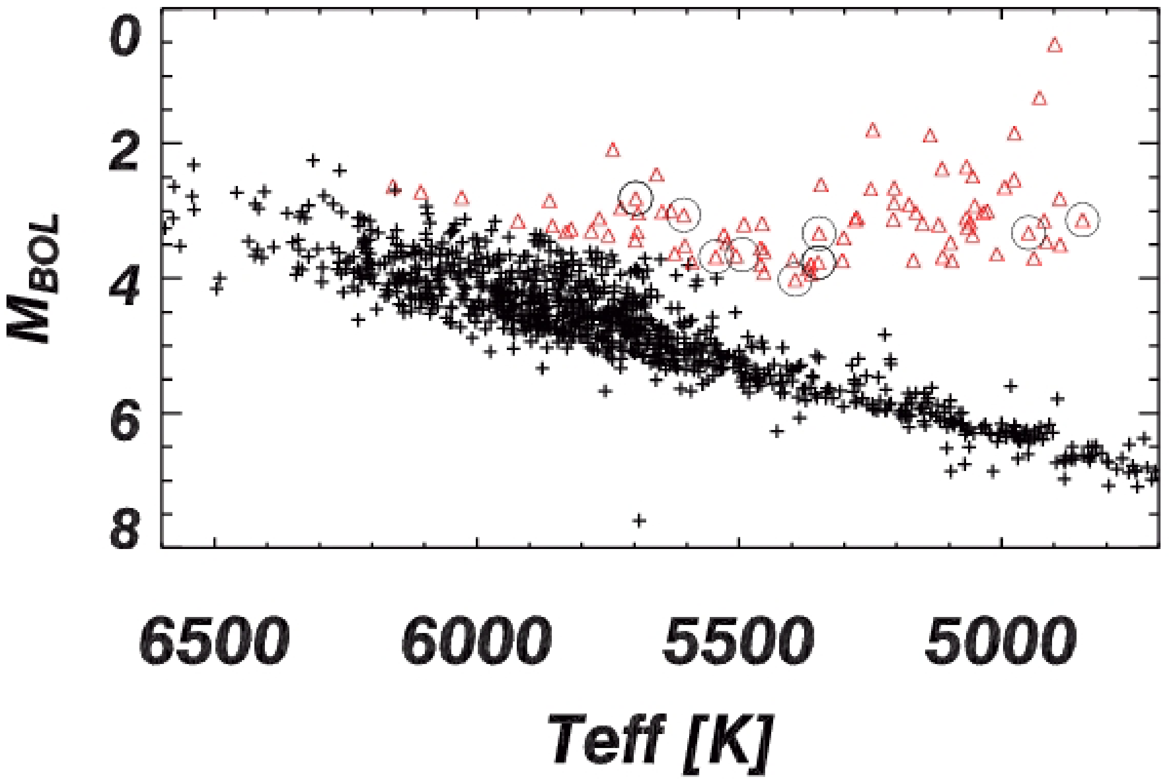


If accretion, then…

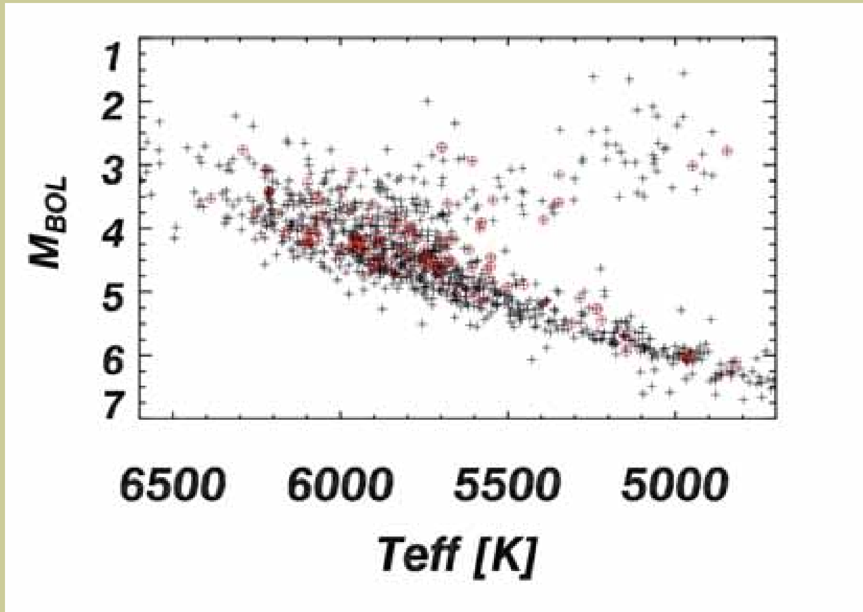
Expect subgiants with diluted convective zones to exhibit lower metallicity

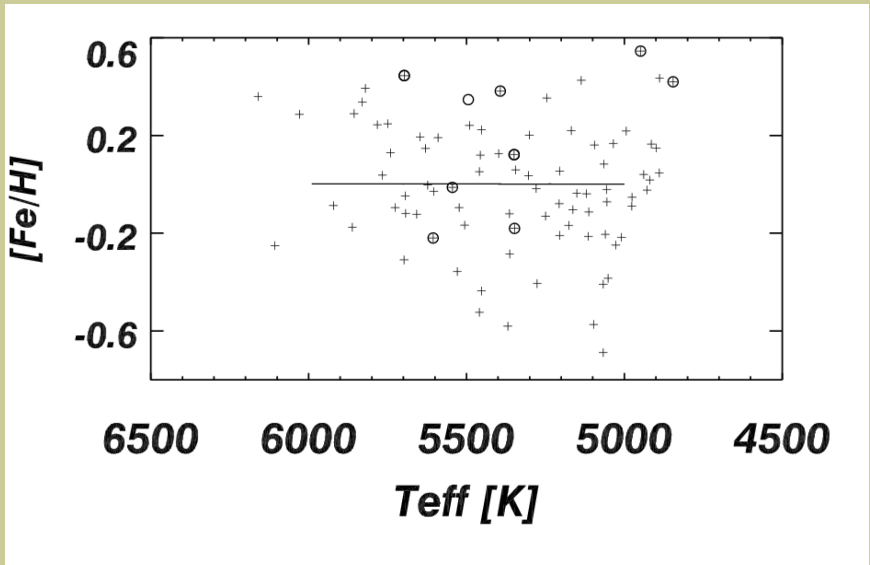
MS F stars, thin CZ **Subgiants, diluted CZ**





0
2
4
6
8
M_{BOL}
6500
6000
5500
5000
Teff [K]



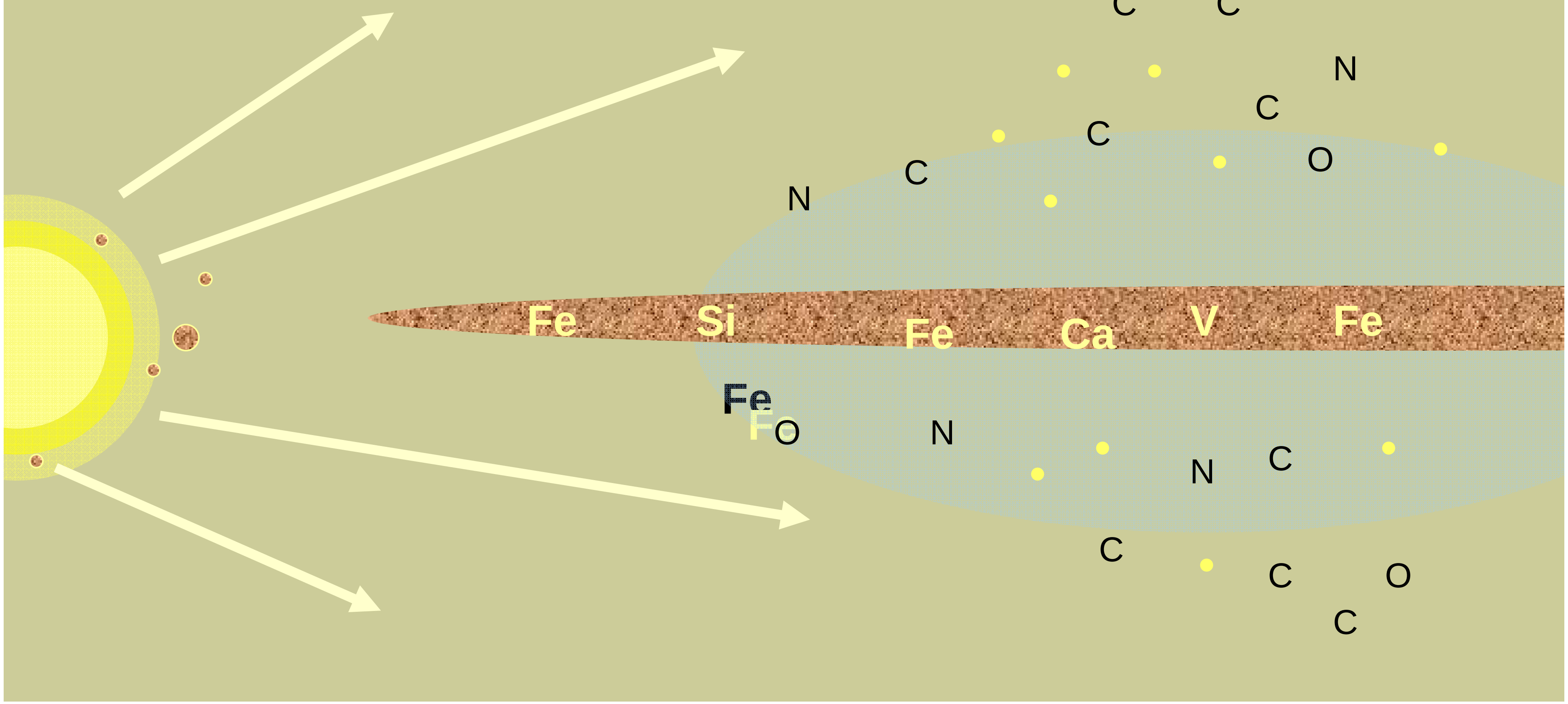


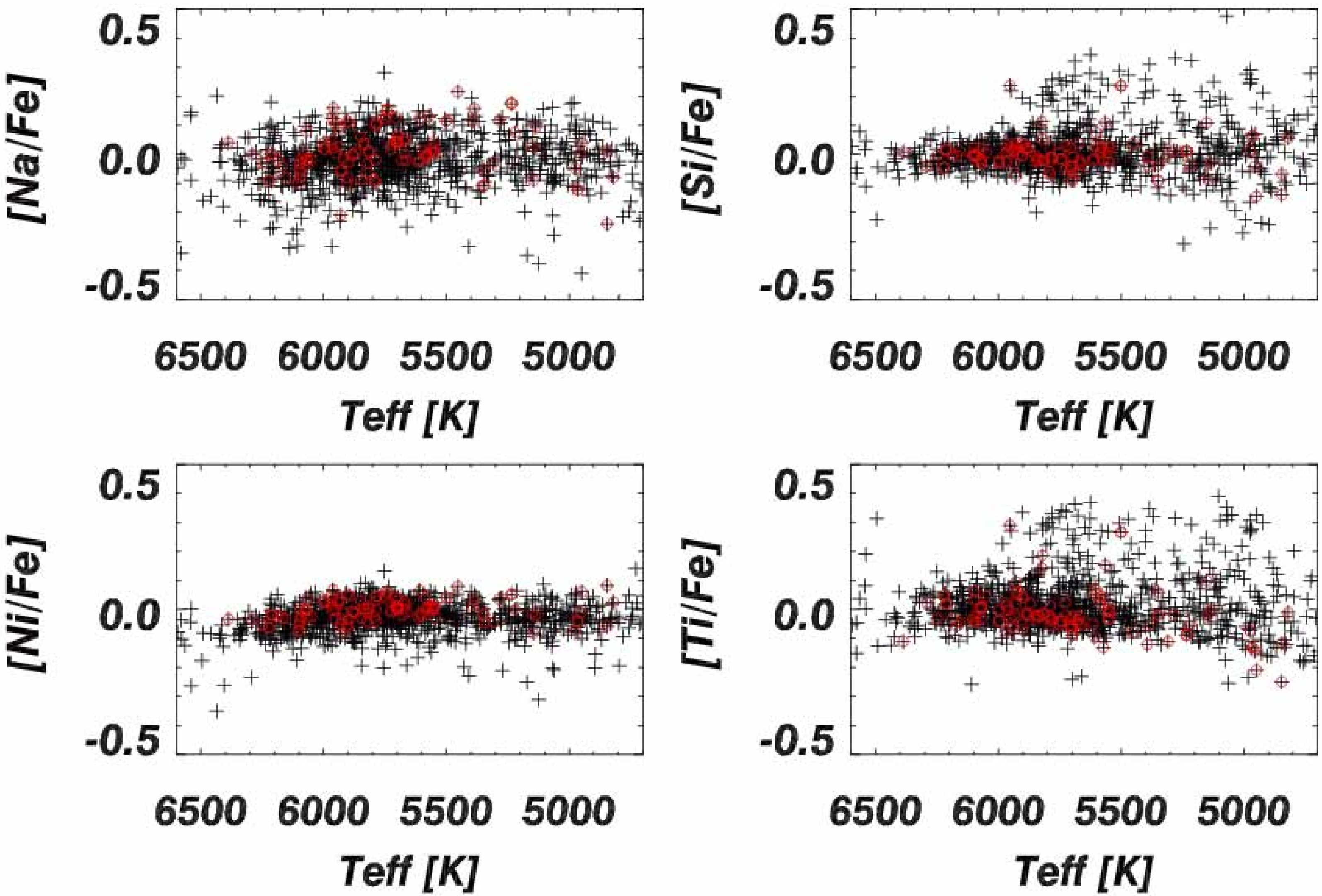
- **Subgiants without planets have same metallicity distribution as MS stars without planets!**
- **Subgiants with planets have same metallicity distribution as MS stars with planets!**

No metallicity gradient across the subgiant branch

If accretion, then…

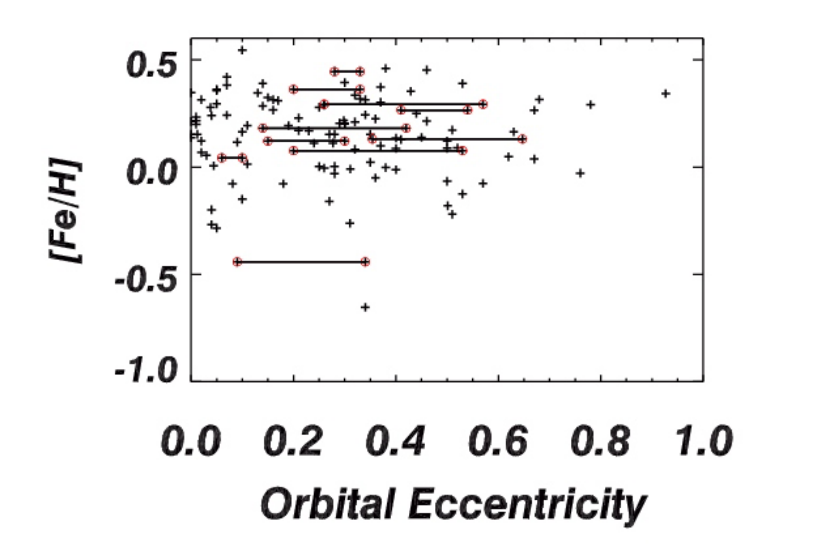
Accreted material mixes in convective envelope polluting the stellar photosphere and producing high metallicity

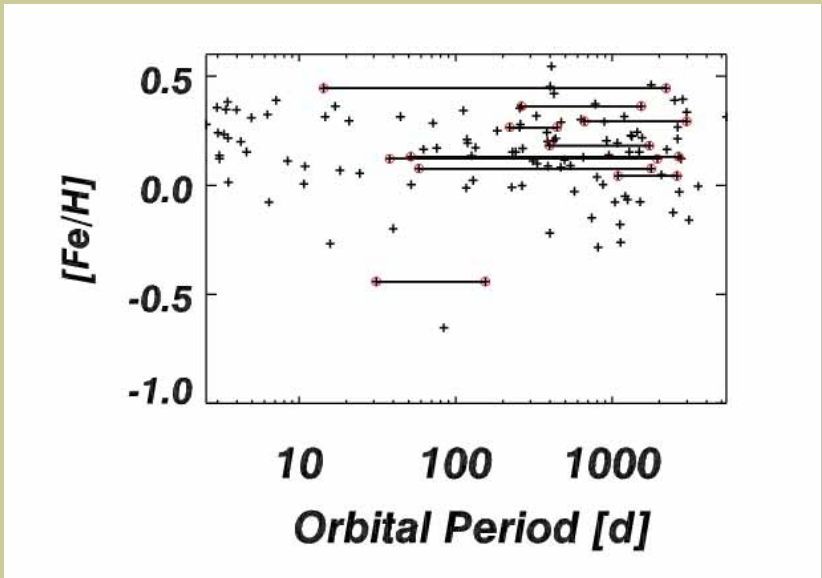



[Na/Fe]
[Si/Fe]
[Ni/Fe]
[Ti/Fe]
0.5
0.0
-0.5
6500
6000
5500
5000
Teff [K]

If accretion, then…

Might expect stars with planets in closer orbits or high eccentricity orbits to show higher metallicity than stars with planets in more distant orbits.





(Multi-planet systems connected with lines)

No corrrelation between metallicity and orbital eccentricity or orbital period.

Stars with planets are metal-rich, even when planets are in wide orbits!

No accretion signature observed!

No trend in max metallicity with CZ depth

No tendency for planets at large semi-major axes to exhibit lower metallicity

Subgiants with ESP's are as metal-rich as main sequence stars.

While accretion certainly takes place, these findings imply high metallicity throughout star and point to initial conditions as most important factor in observed correlation. Supports core accretion scenario.

Summary

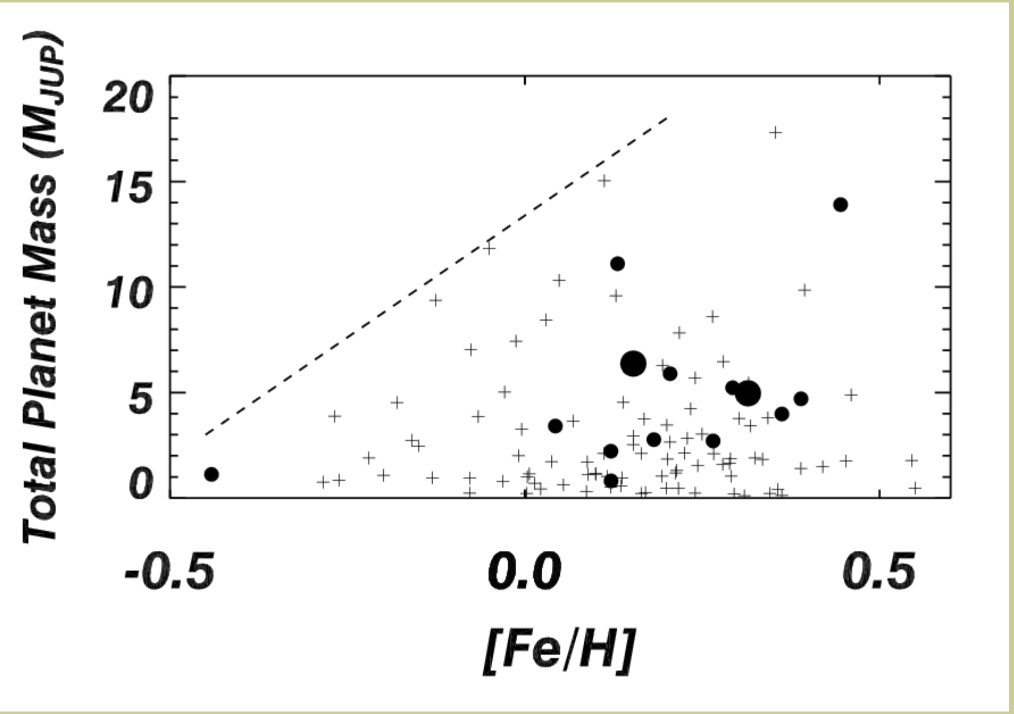
1) Planet occurrence depends on the metal content of the host star.

Only for systems that have undergone migration?
Only for gas giant planets?

2) No evidence for accretion as the underlying mechanism for metal enrichment in stars with close-in gas giant planets.

Suggests initial high metallicity is key factor for formation in Doppler-detected systems

Other Metallicity correlations:



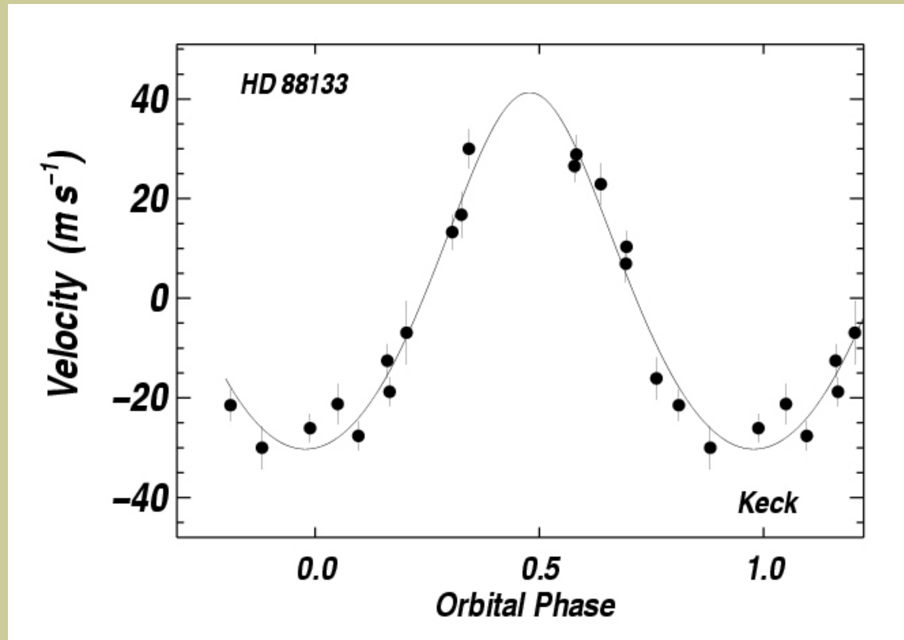
▪Planet-bearing stars with [Fe/H] > 0 are 3x more likely to have multi-planet systems than planet-bearing stars with [Fe/H] < 0

▪***Total planet mass*** appears to be correlated with metallicity

Metal-rich disks nurture the development of many planets and the total disk mass locked up in planets is higher.

Exploiting the Planet-metallicity correlation

Hot Jupiter Search: "N2K"



Fischer, Laughlin, Butler Marcy (NASA / NOAO Keck)

Greg Henry (Photometric Follow-up)

Ida, Sato (Japan: Subaru)

Minniti (Chile: Magellan)

Photometric Light Curve

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Fractional dimming is proportional to the ratio of the cross-sectional area of the planet and star.

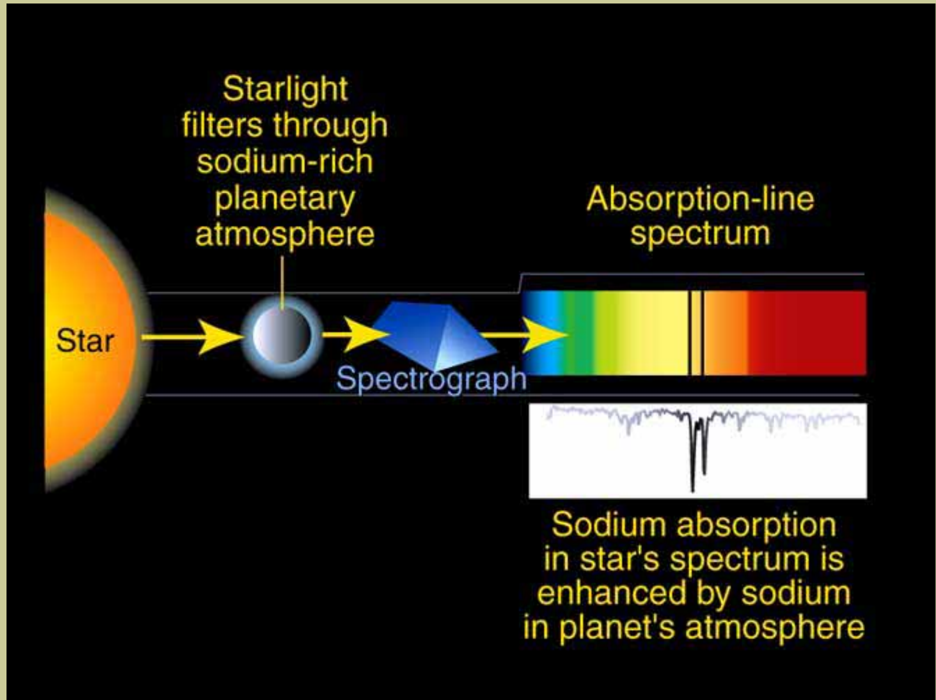
Transiting planets offer an opportunity to observe planetary atmospheric constituents

HST observations of HD209458:

• Light curve with a precision of 1/10000; sufficient to detect moons or rings

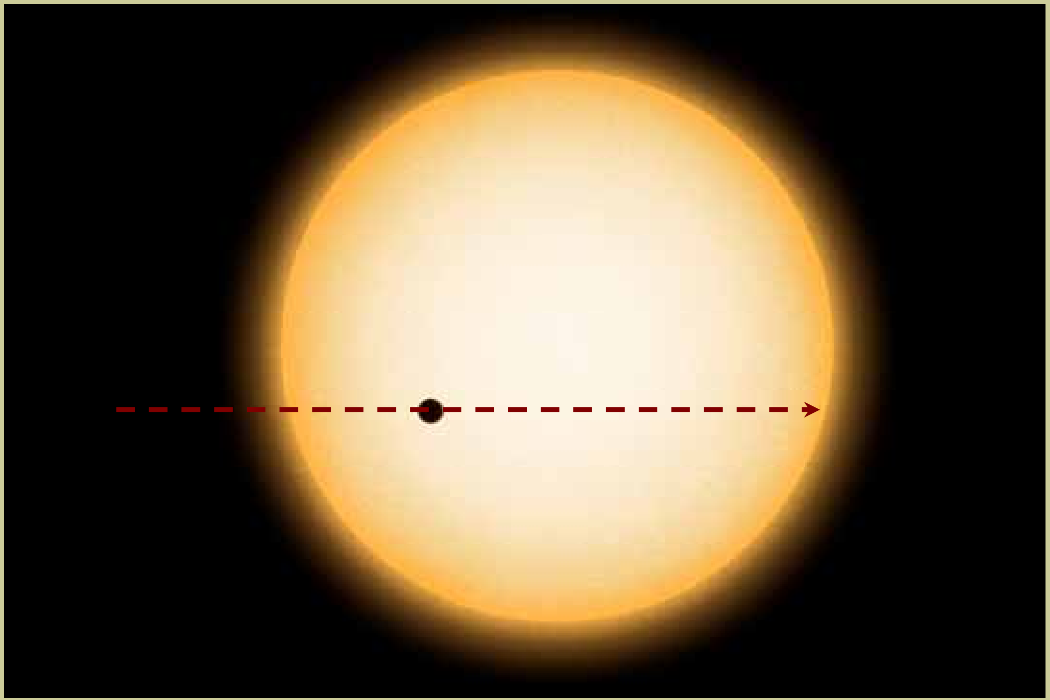
• Na in the upper atmosphere

• An extended H exosphere from Lyman α observations



Success for the Subaru N2K program!

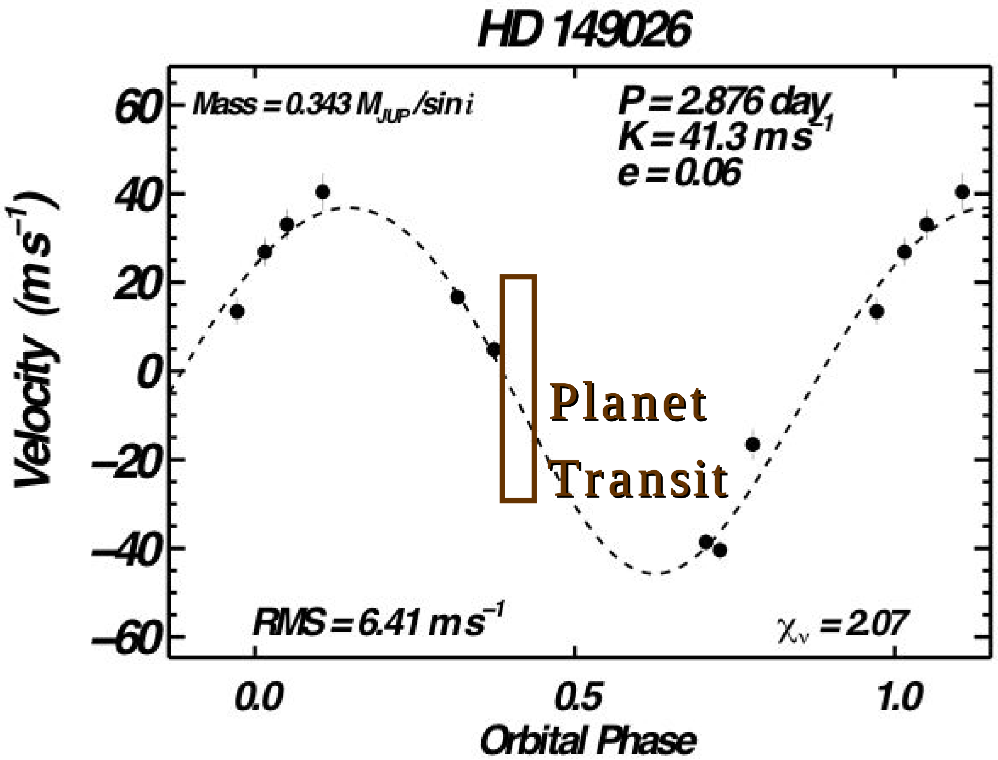
Sato et. al. HD149026b: a transiting planet with a massive core.



An HST proposal for Director's discretionary time was just approved to follow up and look for a Lyman-α exosphere.

P.I. Jeff Valenti STScI

Co I's: Bun'ei Sato, Ron Gilliland, Debra Fischer



Orbit:

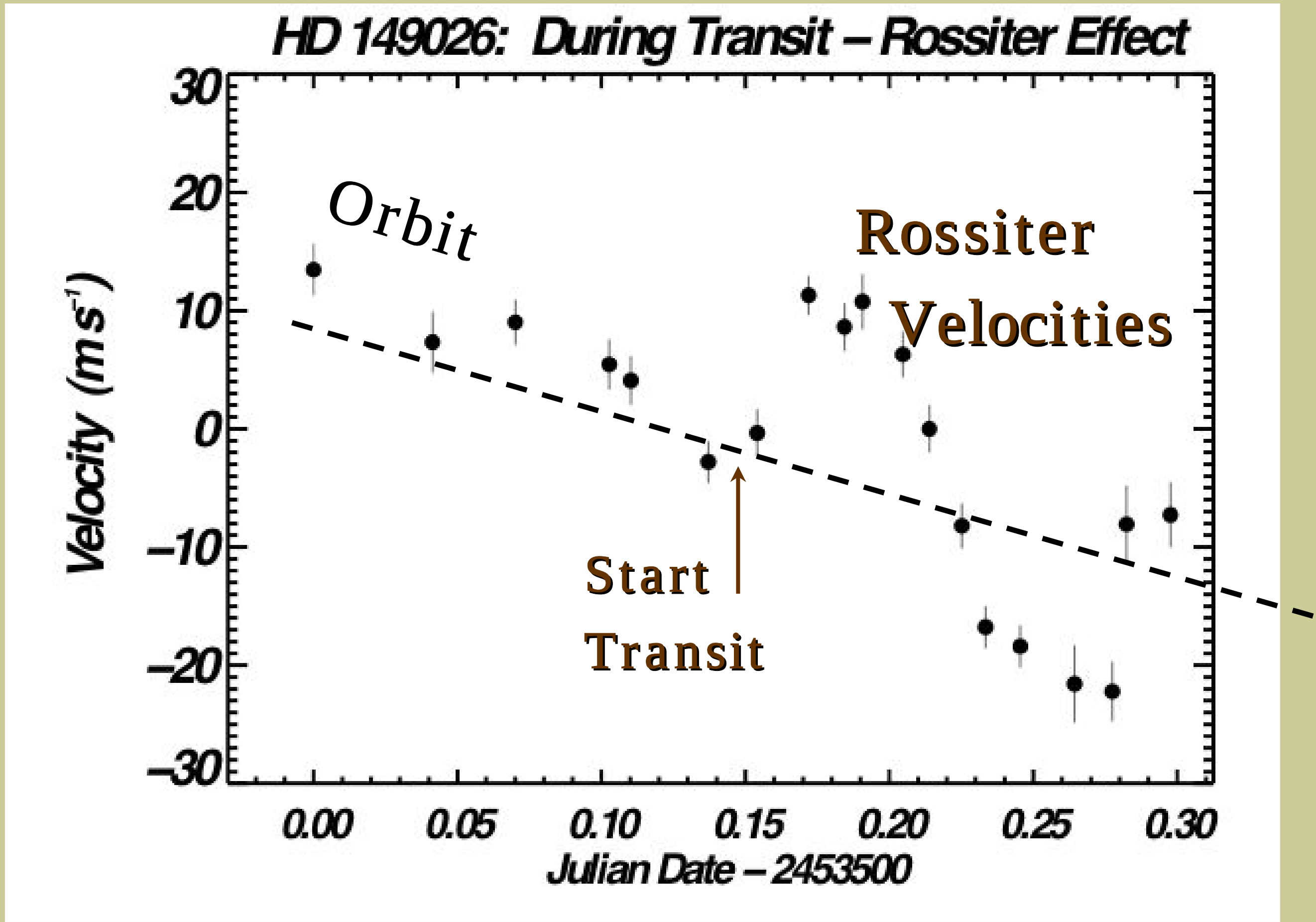
P = 2.876 d

K = 41.3 m/s

Circular

$M = 0.34\ M_{JUP}$

$= 1.14\ M_{SAT}$



10 m/s: Small Planet.

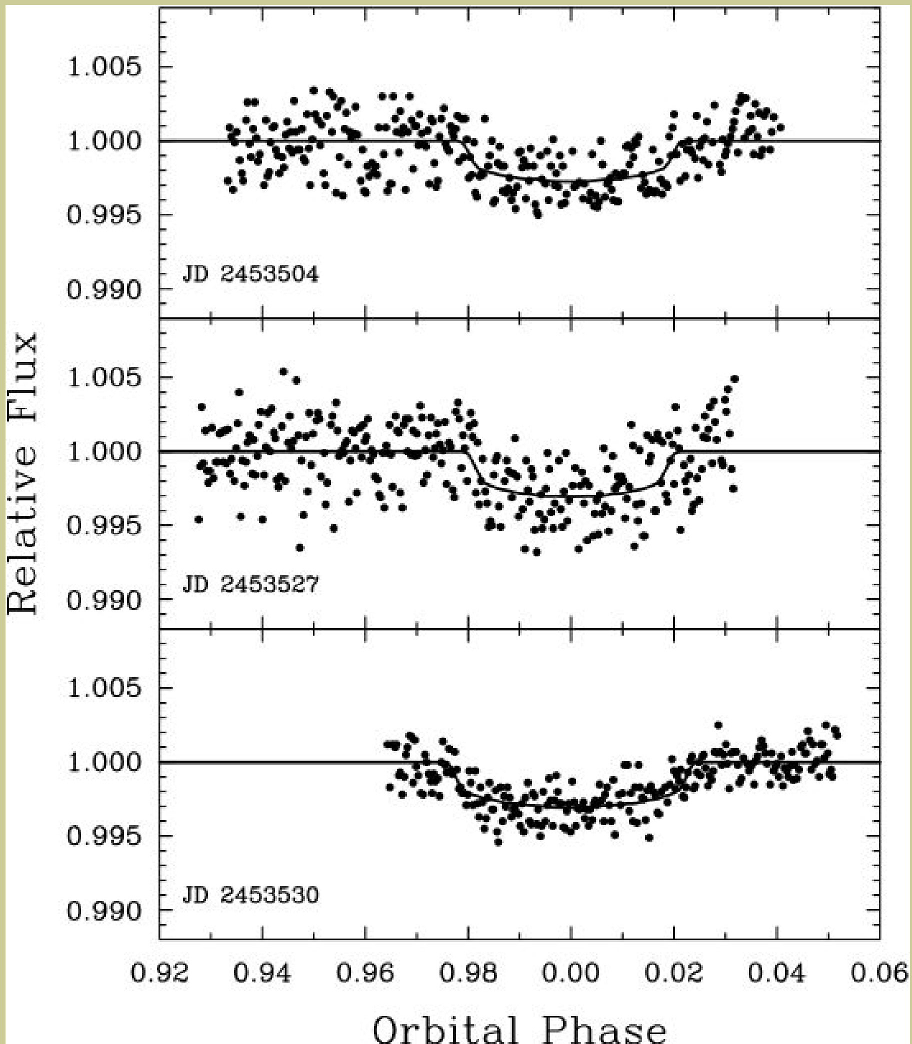
Velocities and photometry modeling now underway by Aaron Wolf and Greg Laughlin

Checking for:
Spin-Orbit Alignment

[See poster by Yasuhiro Ohta: on modeling the Rossiter effect]

A Year in a Weekend!

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Photometry:
Three Transits

3.0 millimag ->
$A_{PL} = 0.0028\ A_{star}$

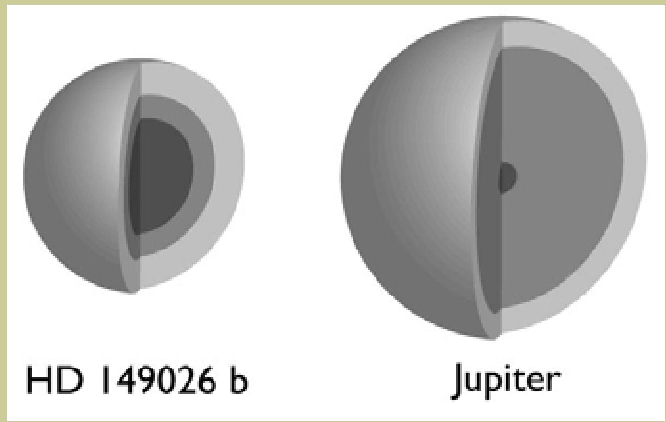
$R_{PL} = 0.053\ R_{Star}$

G. Henry

[See poster byHeather Knutson, modeling HST light curves]

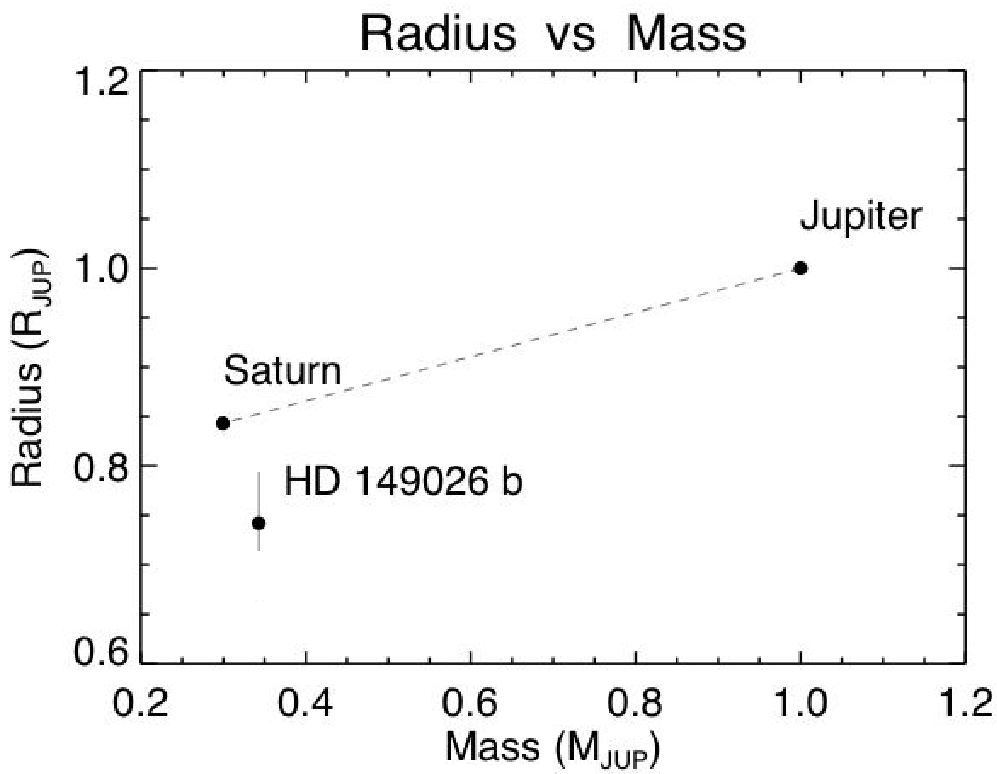
Vital Statistics

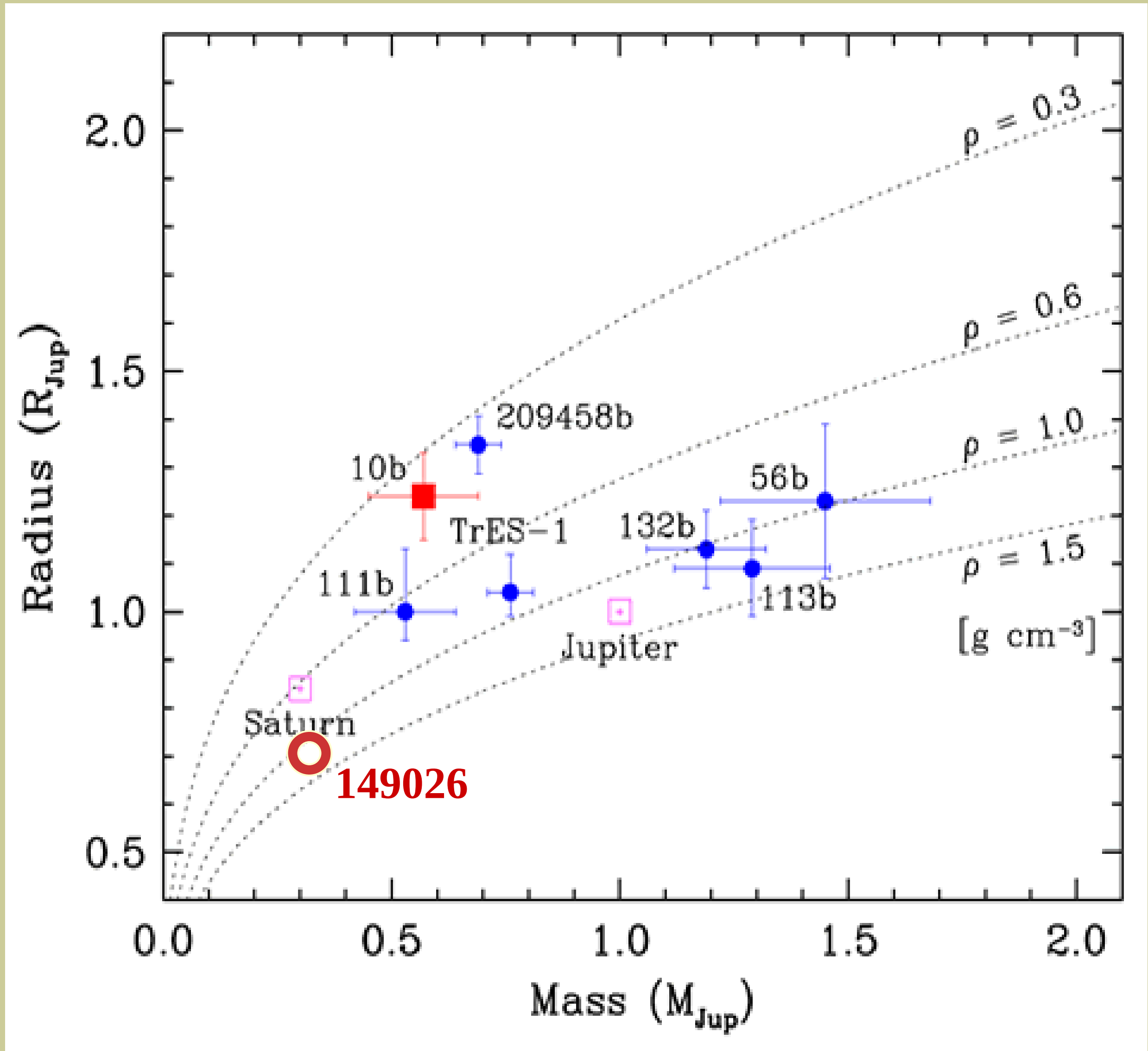
- Star is bright: V = 8.15
- P = 2.8765d
- 3 mmag transit depth
- $M = 0.36\ M_{JUP}$
- $R_{PL} = 0.72\ R_{JUP}$



Modeling the Core:

ρ=10.5 gm/cm^3	ρ=5.5 gm/cm^3	M_{CORE}
0.594	0.662	89.3
0.681	0.745	74.5
0.769	0.818	60.0
0.866	0.905	43.6


Radius vs Mass
1.2
1.0
0.8
0.6
Radius (R_{JUP})
0.2
0.4
0.6
0.8
1.0
1.2
Mass (M_{JUP})
Jupiter
Saturn
HD 149026 b

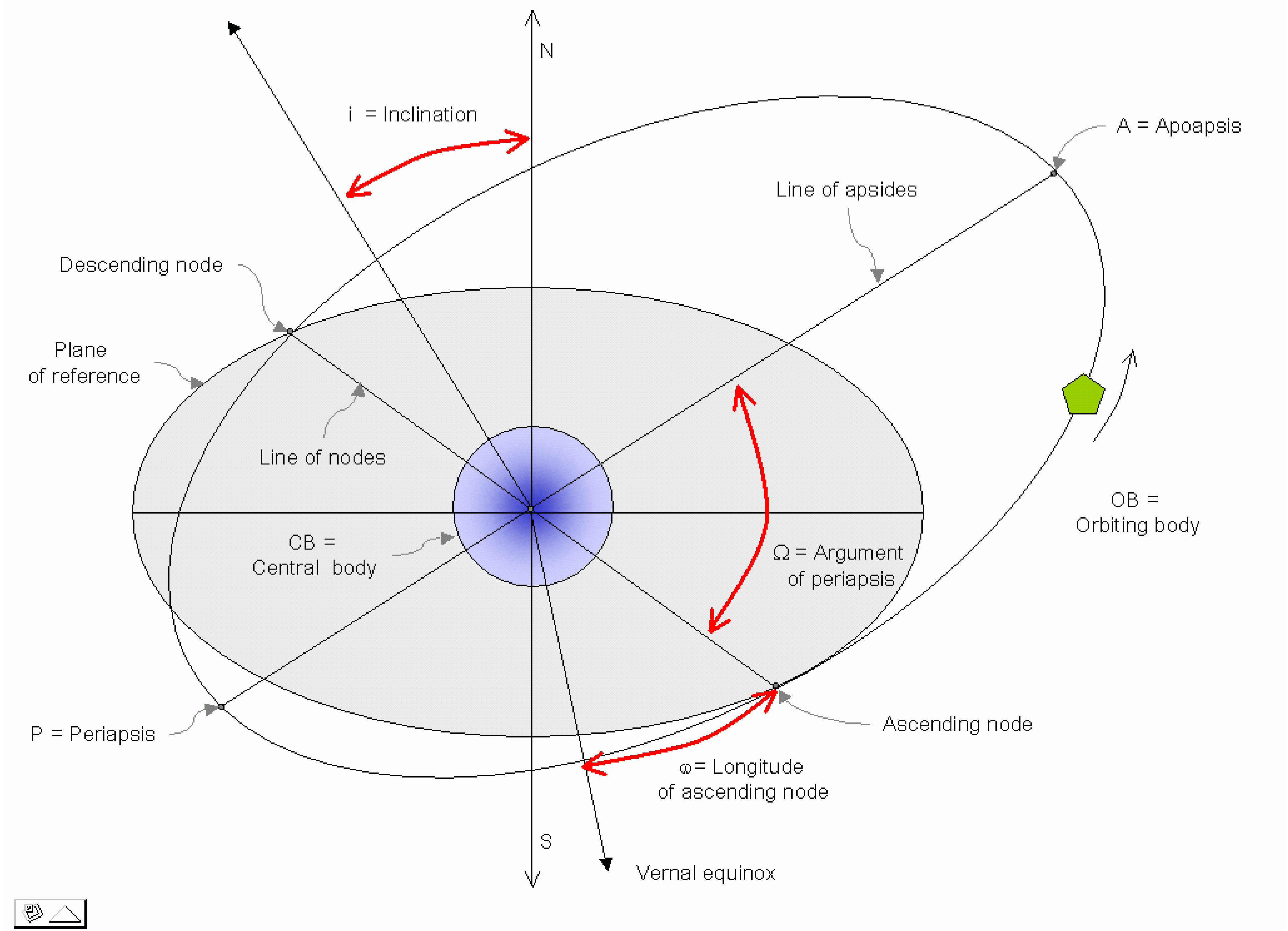


Radius (R_{Jup})
Mass (M_{Jup})
0.0
0.5
1.0
1.5
2.0
ρ = 0.3
ρ = 0.6
ρ = 1.0
ρ = 1.5
[g cm^{-3}]
209458b
10b
TrES-1
111b
132b
56b
113b
Jupiter
Saturn
149026

Important lessons from this discovery

1) It is unlikely that this planet would have been found by a photometric transit survey. Symbiosis between Doppler and photometric observations led to this success

2) Unlikely that this planet would have been found without the Subaru contribution of telescope time: Symbiosis between Japanese and US astronomers


N
i = Inclination
A = Apoapsis
Line of apsides
Descending node
Plane
of reference
Line of nodes
OB =
Orbiting body
CB =
Central body
Ω = Argument
of periapsis
P = Periapsis
Ascending node
ω= Longitude
of ascending node
S
Vernal equinox